AN OPTIMAL ENGINEERING PLANNING MODEL FOR WATER RESOURCES DEVELOPMENT

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By

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CERTIFICATE

Certified that this work 'An Optimal Engineering Planning Model for Water Resources Development' by K. Ranga has been carried out under my supervision and that this has not been submitted elsewhere for a degree.

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(K. Ranga)

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A_{kt_s}	-	Returns from project k in period t_s
AL_t	-	Maximum irrigable land with supply from more than one project
a_{ij}	-	Arc connecting node i to node j
b_{ij}	-	Rate of return by passing 1 Hect-m of water through arc a_{ij} (in out-of-Kilter algorithm)
b_{kt}	-	Decision variable of reservoir k in period t (linear decision rule)
C_{kt_s}	-	Capital cost of project k in year t_s
C_{ij}	-	Decision variable in duality theory
	=	$\pi_i - \pi_j - b_{ij}$
D_{kt}	-	Demand for water at project k in period t
E_{kt}	-	Evaporation losses from the surface of reservoir k in period t
F(r)	-	Cumulative distribution function P(R r)
G	-	Reservoir index for independent reservoirs in Cauvery basin: G = (1,2,5,9,13,30,35,37,42,43,47,49, 53,55,58,62,66,71,76,79,83,89,90,95)
g_{kt_s}	-	Decision variable
	=	1 if project k is introduced in period t_s
	=	0 otherwise
H	-	Reservoir index for dependent reservoirs in Cauvery basin: H = (17,21,63,69,81,86,93)

I_{kt} - Irrigation water supply from reservoir k in period t

i - Source node index

j - Sink node index

k - project index ($k = 1,2...m+n+1,...M+N$)

k_{up} - Sub-set of respective upstream reservoirs

k' - Numbers of scale of projects that can be constructed at a site (mutually exclusive sub-set)

M - Total number of surface water projects in the basin

m - Number of existing surface-water projects in the basin

N - Total number of well-field-units in the basin

n - Number of existing well-field units in the basin

O_{kt_s} - Operation, maintenance and replacement costs of project in year t_s

P_{kt} - Power water supply from reservoir k in period t

P - Probability density function

Q - Reservoir index for independent reservoir

R - Reservoir index for dependent reservoir

R_{kt} - Inflow to reservoir k in period t

R'_{Qt} - Fraction of release X_{Qt} from upstream reservoirs Q in period t that enters the reservoir R

R_i - Discrete value of stream flows

$\bar{R}$ - Mean stream flow

r - Discount rate

\- Also stands for particular value of stream flow

S_{kt}	-	Storage in reservoir k in period t
S_{kt}^{min}	-	Minimum storage in reservoir k in period t
s_R	-	Standard deviation of stream flow
T	-	Time horizon in years
t	-	Time index t = 1,2 t = remainder of $t_s/2$ for $\frac{t_s}{2} \neq 0$ t = 2 otherwise
t_s	-	Time index ($t_s = 1,2,3...T$)
V_{kt}	-	Maximum storage capacity of reservoir k
W_{kt}	-	Municipal and industrial water supply from project k in period t
X_{kt}	-	Release from project k in period t
x_{ij}	-	Flow in arc a_{ij}
y_{ij}	-	Marginal value of increasing H_{ij} by one unit
z_{ij}	-	Marginal value of decreasing L_{ij} by one unit
Z	-	Objective function
α	-	Vector of probability
γ_1	-	Value of cumulative distribution function
γ_2	-	Value of cumulative distribution function
δ_{kt}	-	Evaporation parameter of reservoir k in period t
η_{kt}	=	$1 - \delta_{kt}$
ω_{kt}	=	$1 + \delta_{kt}$
ω_i	-	Return per unit quantity of water supplied for irrigation (Rs./Hect-m)
ω_p	-	Return per unit quantity of water supplied for power (Rs/Hect-m)

ω_W - Return per unit quantity of water supplied for municipal & industrial supply

Ψ_{Qt} - Decision variable: fraction of release from reservoir Q in period t, that becomes stream flow

λ_{t_s} - Discount factor

- $1/(1+r)^{t_s}$

$\sim$ - Dual variable in out of Kilter algorithm associated with quality constraints of the primal problem

$\epsilon_{(m)}$ - Change in the quantity of flow to the node m

SYNOPSIS

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AN OPTIMAL ENGINEERING PLANNING MODEL FOR WATER RESOURCES DEVELOPMENT

The primary purpose of water resources analysis is to provide the information necessary for optimal development of water resources systems. In recent years such analysis and design have been greatly helped by the use of systems analysis and operations research techniques. The optimal development of water resources system consists of two basic issues: a) Scheduling of promising projects and b) Operation policy of system to achieve the required objective. These two problems are solved using mathematical programming method. Scheduling problem decides which of the sub-set of projects is to be selected, their sequence of construction and timing of introduction of projects into the system to provide the capacity. Operation policy of the system gives the releases from different projects of the system to meet the demands specified. The demand for water is met with either by surface water supplies or ground-water supplies or both. Thus the model analyzes the integrated use of ground and surface supplies.

The locations of potential dam sites and well-field units are determined by the topography and geology of the basin, aquifer characteristics, runoff statistics and recharge potential of the basin.

In the model the following assumptions are made:

1) Time scale of introduction of a new project is chosen as one year. Each project selected, becomes the part of the system at the beginning of the year.

2) Each project can be constructed to three different scales. Each scale of construction is considered as a separate project.

3) Hydrology of each sub-basin is known.

4) The present and future demands for various uses - irrigation, hydropower, municipal and industrial supply are known over a planning horizon.

The optimization problem is formulated as a zero-one mixed integer programming problem. The problem is decomposed into a set of feasible combinations. Each feasible combination is solved by implicit enumeration using Little's Branch & Bound algorithm. The optimal returns of each feasible combination is determined by Fulkurson's out-of-Kilter algorithm. Then that combination of projects which gives the maximum value of returns (present value of net benefits) is selected as the optimal sub-set.

The model is extended to incorporate stochastic environment taking inflows to the system as random variables. Chance-constrained approach is adopted for the stochastic formulation. Using linear decision rule of Revelle et al. and probability distribution of stream flows, optimization problem is solved, for the confidence level as specified by management.

Both evaporation losses from the surface of reservoirs and return flows from irrigated areas and municipal and industrial supplies are included in deterministic and stochastic models. The return flow coefficients of 0.40 for irrigation and 0.70 for M & I supplies are adopted. The evaporation losses are taken as constant in the season of the year.

The model has been proved as an efficient technique for scheduling and sequencing of projects and in determining efficient operating policy. The model is flexible to incorporate any institutional constraints like contingent and compound projects.

Integer values which have zero-one variables indicate which projects should be constructed, and to what capacities in order to meet the demands. Activity levels of continuous variables indicate the quantities of water released or pumpages from the projects of the system.

The model is formulated for the seasonal storage requirements. In the model the year is divided into two sessions - Kharif (May to October) and Rabi (November to April).

With access to a large enough computer it is possible to use this model over many time periods depending upon the characteristics of inputs and demands of the basin.

The methodology is applied to the planning process of Cauvery river basin (Karnataka, India). The basin under consideration drains an area of 36240 sq. km. The main physiographic divisions of the basin are (a) Western Ghats (b) Plateu of Karnataka. The delta region of basin which is in Tamilnadu is not considered in the analysis. However, the mandatory releases for down stream uses are incorporated by suitable constraints.

The basin consists of a number of tributaries. There are 24 potential dam sites in addition to the existing 12 reservoirs. There is a provision for using ground water for supplementing irrigation in certain regions of the basin. The demand comprise of irrigation, hydropower and municipal and industrial supplies.

At each location of the project (either surface water or groundwater), three scales of development are considered and each scale is considered as a separate project. For each project capital cost, operation, maintenance and replacement costs and annual maximum returns are considered.

The problem is solved on IBM 7044/1401 system. The results indicate the site and timing of projects and the operation of the system for maximizing present value of net benefits.

Sensitivity analysis was conducted for different parameters namely discount rates, time horizon, and capital costs of the projects. It was found that the time horizon of more than 30 years has no effect on the scheduling and sequencing of projects. Social discount rates of 3%-5% are used in the model and results are presented.

For the successful application of the model a considerable input from economists, engineers and other experts familiar with local situations is required. It can be concluded that the model serves as a powerful methodology for the investment policy problems.

The model can be extended for stochastic demand pattern on the system.

Chapter 1

INTRODUCTION

1.0 General

For a long period, conventional methods were employed in the analysis of water resources system. In studying river basins, which are enormously complex, various interacting physical, economic, social and political systems should be taken into consideration. At the outset, for systems study of a river basin, an approach is required which will reduce this complexity to the level at which the systems analyst can perceive the major relevant interactions in that basin. The appropriateness of an approach depends upon the systems analyst and his previous experience and the nature of physical system under consideration.

In recent years there has been a growing interest on the part of government agencies, planners, engineers and economists in improving the methods of analysis of water resources systems. Much thought and writing has been devoted to the subject, but most of it is problem oriented. Many reports and research articles have been published which are based on special situations and technical conditions.

Water resources development is required to minimize the discrepancy that exists between natural supply of water in time & space - both in quantity and quality - and the demand for it. To bridge this gap in demand and supply it is necessary to construct hydraulic structures and specify their operational policy.

Water resources systems include physical, economic, political, legal and ecological aspects. It is necessary to identify and integrate all these aspects in order to achieve comprehensive development of water resources.

In the present study an attempt is made to use systems analysis to analyze alternate investment patterns in water resources projects and to present efficient operation policy. The result of this work is a new planning model based on branch and bound algorithm combined with out-of-Kilter algorithm for scheduling and sequencing of water resources projects. Use of this method is demonstrated by applying it to the Cauvery river basin. It is assumed that hydrology of the basin and other institutional and budgetary constraints are known.

1.1 Planning Horizon

A review of the performance of existing water resources projects shows that 10-15 years or more elapse between the conception of a need and the full utilization of the system. Apart from political hassal period in which, rights, responsibilities and obligations of all concerned are thrashed out in a

political environment, present day water resources systems require 5-10 years or more as construction period. Water resources systems are quite durable. Systems that were built centuries ago are still in use in many parts of the country. However, for economic analysis, a planning horizon of 30 years is taken. Planning horizons of 40 and 50 years are also examined.

1.2 Discount Rate

The classical economic theory views interest rate as a rate of discount on future goods and services whose level is determined by balance of considerations of time preference and productivity (Mao, 1969).

The concept of interest rate is of considerable abstraction since it is observed that in the market a number of different rates vary primarily with length of time and type of security offered. The theoretical interest rate refers to riskless investments and may vary with time span.

In case of water resources system there is another important factor to be considered. Huge investments are made during the planning and construction period (Eckstein, 1965). The returns start accruing only after the project is completed or has attained a certain stage of maturity. This major difference in time between the centre of gravity of expenditure

and the centre gravity of returns leads to a requirement of a means of comparing the value of money at different times.

The accepted method is to calculate the discounted return according to some discount rate. What the rate should be, is still a subject of controversy. With long horizons involved, low discount rates aid the feasibility of project while high rates can easily kill it.

When applied to water resources systems analysis, low discount rates are justified. In this study discount rates of 3-5 percent are considered.

1.3 Hydrology

Hydrological variations create a need for dams and reservoirs in order to regulate the stream flow to make it correspond more nearly to the demands imposed upon it. This regulation may be for the purpose of controlling high flows or for augmenting the low flows or for both.

Stream flow is essentially a stochastic quantity. Regardless of regulatory storage provided or manner of its release, there still exists a certain probability that the high flows will not be contained or that there will be insufficient water to augment the low flow.

In the stochastic model of this study, the stochastic aspect is considered and the chance constraint approach is used in the analysis.

Evaporation losses are quite considerable in arid and semi-arid regions. It is estimated that 1.2 m to 1.5 m are lost due to evaporation from the water surface of reservoirs. These are given due consideration in the analysis.

1.4 Water Demands

The demand for water is of two types - consumptive use and non-consumptive use. The consumptive use is generally for agriculture, municipal and industrial supplies. Non-consumptive uses include recreation, navigation, power generation and wild life preservation.

The demands of water are obtained by knowing the irrigable area, type of crops, farm technology adopted, population growth, per capita consumption and standards of living. These demands are estimated sub-basinwise in the entire basin.

The best indicators of the demand pattern over the interval - say a year, is the maximum water demand, D_{max} and minimum demand, D_{min}. The total demand over the interval is the area under the demand curve, $y = d(t)$, figure 1.

$$D = \int_{o}^{T} d(t).dt$$

D is taken in the units of hectare meters.

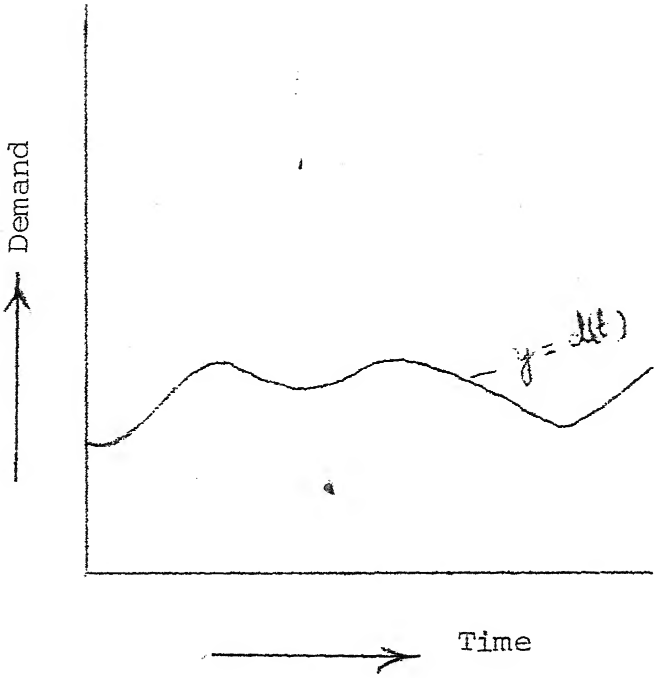


Fig. 1.1. Demand Curve

1.5 Cost Characteristics of Water Resources System Elements

The cost functions associated with various components display 'economy of scale' to a greater or lesser extent, i.e., cost per unit of capacity decreases as the capacity increases (Hall & Dracup, 1970; Hirshliefer et al., 1960). There is nearly always a finite discontinuity of the cost functions at zero capacity. In addition, most components of the system involve very large investments compared with operation and maintenance costs. It is rather difficult to derive generalized expressions for cost functions of dams. At any site there will be substantial fixed costs associated with preparation of site, for construction particularly for foundations and abutments. The relative economy of scale clearly depends on the cost of site preparation and height to width ratio. As pointed by

Hall and Dracup (1970), depending upon the dam site and scale of development, economy of scale could provide a doubling of capacity for as little as 1.2 times the cost or might require twice or more than twice the cost. In many cases with good sites, the physical limitation of stream flow may limit the height long before the cost function reaches a convex segment.

1.6 Water Rates

Returns from system related to water use are even more difficult to treat. Water rates are fixed depending upon type of the use. In arid and semi-arid regions, sufficient quantity of water has to be supplied to provide for the evapotranspiration and to leach salts, if any, accumulated at the root zone. Hence, irrigation requirement is a major demand for water.

In India there exists a wide variety of methods for calculation of water rates supplied to agriculture. These rates vary from state to state, from basin to basin and from project to project. The value of crop at maturity served as a rough guide in fixing irrigation water rates (C.W. and P.C., 1955). Irrigation Rates Committee, U.P., India (1939) reports that the value of water is a function of cost of the supply and increase in the produce from the land irrigated. A fair rate is one which yields adequate profit on out-lay on one hand, and offers sufficient inducement to the cultivator to avail the facility, on the other hand; and also prevents them from extravagance or

waste. The National Council of Applied Economic Research (NCAER, 1959) suggested that whatever be the net benefit, the actual water rate should in no case exceed 50 percent of extra benefits available to cultivators. The actual charge could vary between 20 percent to 50 percent of net benefits.

The system of charging for water according to volume supplied is scientific and rational in nature. But it involves large initial investment on measuring devices and supervisory staff. Moreover, there is the risk of damage as the people may tamper with the meters. It is also readily susceptible to malpractices on the part of the officials.

Though the net benefit method is accepted as a sound basis for fixing of water rates, it is rather difficult to apply it as it involves collection of data on type of crop, yield, prices and cost of production. Generally water rates are fixed depending on the type of crop grown and acreage under different crops. This practice indirectly implies that water rates are fixed on amount of water used, efficiency of irrigation and conveyance from head works to the fields. NCAER recommended that compulsory rate of 15 percent to 30 percent of net benefits is to be levied as water rates. For this purpose, the area would be divided into various groups and net benefits accruing to cultivators are measured for different crops in each soil and each season. Another study in this connection, worth mentioning is: Evaluation of Major Irrigation

Projects - Some Case Studies - Planning Commission, India (1965). The details of finding the water rates from the revenue collected is given in Appendix.A.

Municipal and industrial water rates are taken from the schedule of water rates applicable to the city of Bangalore. Similarly, the revenue of water diverted for power generation is obtained by tariff schedule of Karnataka Electricity Board (KEB).

1.7 Conjunctive Use of Ground and Surface Waters

There is a growing awareness for conjunctive utilization of surface and ground water supplies. As the increased demand for water is not met with surface supplies, the conjunctive use of ground and surface supplies comes into sharper focus. This implies an allocation problem involving both physical and economic parameters and this allocation must be done in an efficient way. The required allocation is best dealt with in the form of two models - a physical model and an economic model. The former enables the physical quantities of available water under varying conditions to be determined and the latter allows the allocation of this water to be made to various demands, subject to given costs and the optimum allocation is determined iteratively to meet the specific objective.

In this dissertation conjunctive utilization is considered implicitly and the model decides when and in what quantity the ground water is to be utilized.

1.8 Return Flows

Not all the water diverted to agriculture is consumptively used by the crops. That part which is not consumptively used runs off the crop land as surface flow or seeps into ground and returns to the rivers as return flow (Maass et al., 1962). Some part of the water which seeps into the ground becomes part of the water called interflow and is essentially available as surface water since the streams, lakes or reservoirs intercept it. The remainder becomes part of ground water supply by the process of deep percolation. Return flow coefficients are estimated for different hydrological units and considered in the analysis.

Similarly not all the water diverted for municipal and industrial supply is consumptively used. Waste water from residential areas and industrial plants after treatment is channeled into surface streams and is also known as return flows. The total return flow from agriculture and municipal and industrial supplies is taken into account.

The various parameters considered above are used in the development of subsequent models.

1.9

Chapter 2 provides a review of current practices on water resources planning.

Conventional analyses are conducted on a partial or project by project basis but the selection and performance of any specific project at any particular time is heavily influenced by the composition of the rest of the projects; Marglin (1963) says 'Planning of water resources development projects is more, even more complex by the impossibility of separating the problem of choosing the optimal input-output bundle from the problem of scheduling the construction of the component increments. We cannot, for example, simply determine the optimal input-output bundle as if the entire plan is undertaken today and then determine the optimal sequence of construction of various phases of the plan. It is often the case that input-output bundle which would be optimal under the assumption that all construction must take place at once is no longer optimal when we remove this restrictive assumption and expand our horizons to include future construction possibilities ...'.

In the past, systems analysis techniques could not be used extensively because of the time and money required for the analysis considering all the components of the system. However, with computing facilities becoming widely available, this is no longer a problem. When huge investments are involved in water resources development it is highly desirable to adopt systems analysis and operations research techniques.

Chapter 3 presents different models which are developed for the sequencing and scheduling water resources projects and

to find out efficient operation policies. Any model developed to solve water resources problems should have the following characteristics:

1. The model must optimize some specified objective.

2. The model should be feasible. It should be possible to set up and solve the model within a reasonable amount of time.

3. The model should be efficient in data use. It should be possible to use the relevant available information and not insist on data which one is not likely to obtain.

4. The model should yield such results which can be understood by those who actually make the final decisions and can be implemented.

5. It should be flexible enough to allow for sensitivity analysis of important parameters. Particularly attention should be given to those parameters which are uncertain in nature.

The development of the investment model in the deterministic environment followed by stochastic model is presented in Chapter 3. Finally evaporation losses are also included in the analysis. The return flows are taken into account in all the models.

The model is applied to a large river basin system - Cauvery basin in South India. The basin features are given in Chapter 5. The results and analysis are presented in Chapter 6 along with the conclusions drawn.

Chapter 2

CURRENT PRACTICES IN WATER RESOURCES PLANNING AND DEVELOPMENT

2.1 Introduction

It has been stated that planning is the process by which society directs its activities to achieve goals it regards as important (Veisman, 1974). However, where available water and related land resources are scarce and the current projected competition among various users is great, it becomes exceedingly difficult for planners to (1) properly define goals and objectives, (2) formulate plans that satisfy competing demands or conflicting objectives, (3) gain the public acceptance of proposed plans, and (4) finally implement and operate a system of facilities so as to meet society's goals (Texas Water Development Board - TWDB, 1968).

Over the past decade, engineers, economists and systems analysts, to the best of their ability and within the limits of computational capabilities, have defined meaningful advanced planning procedures and supporting analytical techniques. Largely, their use has resulted in planning strategies that depend upon the fast computational capabilities of the computer

to evaluate plans and operational criteria identified as attractive by the planner in his attempt to find the optimal strategy. Terms such as minimum cost, maximum return and maximum net benefits have emerged and have been extensively used as the basis for quantifying optimality.

Investment planning requires a determination of the goals and objectives of the government, of operating policies to be followed in future time period and resource requirements of alternative investments.

Any systems analysis model must be designed to interact in two directions - with other such models and with exogenous agencies. Models can be classified as preliminary screening, detailed investment analysis and operating policy models. Flow of information within the systems analysis will be from the preliminary screening to the detailed investment analysis to the operating policy models with feedback from the latter models to the detailed investment analysis model.

There is a voluminous literature on the use of systems analysis and operations research techniques in the field of water resources systems analysis. Available literature can be grouped under two broad categories, a) planning and design of water resources, and b) operation policies of water resources system. Most of the work reported in the last 10-15 years has been devoted to the second category of problem - i.e., finding out operating rules of existing water resources system.

Although operation of single reservoir is well documented, there are very few works in the literature on how to size and operate multi-unit-multi-purpose water resources systems. One of the early works and most extensive work in water resources systems was carried out by Maass et al., (1962). They introduced objectives, defined concepts, used systems approach and mathematical programming methods.

In capital investment planning of water resources projects, there exists both a set of durable high cost projects and a number of demands over some specified time horizon. The scheduling problem considered here is:
(i) which subset of the projects in the basin to select,
(ii) in what sequence to construct the selected projects,
(iii) at what time to bring each of the selected projects into the system, and (iv) to specify the operating procedure in order to meet the demand at every point in the basin and in the planning horizon and to optimize some prespecified objective.

A special case of scheduling problem is the sequencing problem. Whereas, scheduling problems involve project selection, sequencing and timing decisions, sequencing problems involve only project sequencing and timing decisions. Sequencing problem arises when, for example, the projects in the given set must be constructed in order to satisfy the requirements. In this case project selection decisions are obviously not necessary.

Mathematical programming methods have been applied to capital investment problems in water resources systems analysis. Marglin (1963) performed an economic analysis of selection of projects and timing of project construction. Calculus of variation and linear programming methods were used in this analysis.

Buras (1972) discussed the application of mathematical programming methods to the design and operation of multi-structure system. Nayak and Arora (1970) used separable programming technique for finding the minimum capacities of reservoirs in a system designed for flood control, low flow augmentation and recreation. Young, Mosely and Evenson (1969) used pattern search technique for sequencing of reservoirs. Many dynamic programming approaches were presented for sequencing of projects (Morin, 1973; Morin and Esogbue, 1971). Butcher, Haimes and Hall (1969) presented a dynamic programming algorithm to solve a special case of the sequencing problem for certain water supply projects. Burton (1969) formulated an integer programming model of project relation aspect of the capital investment problem. Inventory theory was applied by Manne (1962, 1967) to project timing and project capacity decisions encountered in capacity expansion for developing nations. Mulvihill and Dracup (1974) developed multi-level solution technique to determine the optimum sizes, timing of a conjunctive urban water supply and waste water system. Trott & Yeh (1973)

and Becker & Yeh (1974) applied dynamic programming approach to Eel river basin - Sacremanto, California - for finding optimal sizing and sequencing of multiple reservoirs. But Morin (1973) pointed out that conventional dynamic programming may yield non-optimal solution to sequencing problem. Orlob (1970) discussed the approach taken by planners for Texas water system. Trans Texas Division of Texas water system would comprise of 18 reservoirs, more than 800 km of canal networks. In addition, there would be pumping facilities to raise the water from sea-level to over 1000 m elevation. Their planning problem was:

Given: (1) The location of all reservoirs (2) details of canal net-work (3) schedules for in-basin demand for each reservoir and each junction of the system (4) cost of construction, operation and maintenance of all elements (5) hydrology of supply for each reservoir.

Find: Optimal schedule of projects to meet the specified demands within the prescribed legal, institutional and physical constraints.

The Texas Water resources group used a combination of linear programming, simulation technique, response surface methods. This method was to seek near optimal solutions rather than exact optimal solution to overcome the limits that existed on computation time and computer facilities.

Simulation techniques are applied in the analysis of water resources systems (Maass et al., 1962). Simulation process attempts to reproduce the system as faithfully as resources permit. The computation permits the nonlinear, dynamic, stochastic and feedback responses of the system given all design and operating policies before hand. But the cost of simulation in case of water resources systems involving extensive adjustment of parameters makes this technique prohibitive.

Hufschmidt and Fiering (1966) carried out the systematic simulation study for optimal sizing of reservoirs in a water resources system designed to maximize the return on investment and to meet the schedule of water demands. In the analysis it was assumed that the configuration of dams and operating policy for each dam and hydrology were known. For each combination of dam sizes the simulation gave the revenue from operating the system. Simulation technique was also used by Weiss and Beard (1972) to analyse the water resource problem, namely, (1) which of the specified set of projects should be constructed, (2) how large each of the projects should be, (3) timing of construction, (4) how should the system be operated so as to minimize the capital cost plus operational costs over the planning period.

Techniques of optimization and simulation were merged in the analysis presented by Viessman et al., (1975) to select

the most efficient arrangement of components for regional water resources development and management.

O'Laoghaire and Hemmelblau (1971) presented method for optimal capital investment in expansion of an existing water resources system. New approach was presented using zero-one programming and network flow algorithms. Deterministic hydrology was used in the analysis for sequencing of surface supply projects.

Ground water aquifers have also been long recognized as important sources of water. However, in the past no consideration was given for the interaction between surface and ground waters and to establish a rational basis for the development and use of subsurface storage in water resources development. In the last decade many investigators have given the operating policies for conjunctive use of surface and subsurface supplies. The concept of conjunctive use of all sources of water has been developed in recent years (Tyson and Weber, 1964; Koenig, 1963, Dracup, 1966; Rogers and Smith, 1970).

Chun et al., (1964) formulated alternative plans to meet the estimated schedule of future water demand over a planning horizon of 25 years. The demands could have been met entirely through an all-surface distribution system or by all ground water system or by a combination of these.

Dracup (1966) used linear programming method to find optimum policies for conjunctive use of ground and surface waters. Hatfield and Pattison (1970) applied mathematical programming approach for optimal development of surface and ground supplies in Hunter Valley Basin, Australia. A comprehensive review on conjunctive use was given by Milligan (1970). A chance constrained method was used by Smith (1970) for the conjunctive use of surface and ground water supplies to meet the irrigation requirements over a planning horizon.

For a given set of hydrological data and aquifer characteristics, the optimization of the solution of the conjunctive use system involves the solution of three problems:

(a) determination of design capacities for surface facilities including recharge facilities,

(b) determination of the system service area,

(c) determination of operating policy specifying reservoir releases and aquifer pumpages.

There is a voluminous literature on the operation procedures of reservoirs. (Revelle et al., 1969; Nayak and Arora, 1970). Most of the literature available on investment policies in water resources systems deals with a specific economic situation or a particular institutional constraint.

Additional difficulty with the literature available in this field is that it originates from advanced countries where the economic and institutional constraints are quite different from those of the developing countries.

From the brief summary of literature review it can be concluded that the systems approach has been used in the field of water resources engineering and problems have been solved using programming methods and simulation techniques. However, only a few investigators have considered the random nature of inflows and demands of water. Moreover, evaporation losses which are important especially in arid and semi-arid region in the efficient management of water resources have not been given due attention in the optimization models.

Here an attempt is made to formulate the optimization model for investment decisions and to obtain operating rules for different components of the system. The model is structured as a mixed integer programming problem with integer variables taking the values either zero or one.

The details of models are presented in Chapter 3 and solution techniques are presented in Chapter 4 which also presents the salient features of computer programme.

Finally in Chapter 5 the model is applied to a large scale water resources system, namely, Cauvery river basin (South India) and results and discussions are presented in Chapter 6.

Chapter 3

THE MATHEMATICAL MODELS

3.1 Introduction

The optimal development of a water resources system is formulated in mathematical terms by stating an objective function to specify the social goal and constraints to satisfy the different conditions imposed on the model. The locations of different projects are assumed to be determined by the topography, hydrology and geological characteristics of the basin. The criterion for the choice among alternative system plans can be stated as: select that investment programme and operating policy of the system which will maximise the present value of net benefits, subject to various constraints. The mutual interaction of various units of the system at any point in the planning horizon is implicitly taken care of in the model.

The problem under study concerns, which of the projects to be built, at what time and how to operate the system as a whole.

The following assumptions are made in the analysis: a) In investment analysis, a year is taken as time scale of introduction of any project into the system (Weiss and Beard, 1970; Butcher, Hall and Haimes, 1969; O'Lagaire and Himmelblau, 1971).

b) The demands are taken as deterministic variables. That is, the demand at any point of time is known with certainty.

c) In power-generation constraints, the head on the turbine is taken as constant.

Three different models are considered for the study. First model deals with deterministic parameters. Stochastic nature of inflows is considered in the sub-sequent model followed by a model which incorporates evaporation losses from the reservoir surfaces. The models are solved using mathematical programming techniques presented in Chapter 4.

3.2 Deterministic Model

Consider a set of M surface water projects and N groundwater projects, each project can be scheduled for construction in any one of t time periods ($t = 1,2,\ldots T$). If A_{kt_s} denotes the returns from project k in period t_s (where $k = 1,2,\ldots (M+N)$), the problem is to maximize total net benefits from construction of some or all of the above projects, subject to various constraints. The benefit from the system is a function of project sizes as well as their operating policies. A model representing this objective results in a mixed integer programming problem, where certain variables take only zero or one values and other variables take real values.

The problem can be stated mathematically as:

Maximize Z, where

$$Z = \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{k=1}^{m+n} A_{kt_s} + \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{k=m+n+1}^{M+N} g_{kt_s} A_{kt_s} - \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{k=m+n+1}^{M+N} g_{kt_s} C_{kt_s}$$

$$- \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{k=1}^{m+n} O_{kt_s} - \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{K=m+n+1}^{M+N} g_{kt_s} O_{kt_s} \qquad (3.2.1)$$

Subject to

1) Budgetary constraints

$$\sum_{k=m+n+1}^{M+N} g_{kt_s} C_{kt_s} \leq M_{t_s} \quad \text{for all } t_s \qquad (3.2.2)$$

2) a) Institutional constraints

$$\sum_{k=m+n+1}^{M+N} g_{kt_s} \leq b \quad \text{for all } t_s \qquad (3.2.3)$$

i.e., number of projects that can be introduced into the system in any year t_s will be at most equal to b, a prespecified number.

b) $$\sum_{t_s=1}^{T} \sum_{k' \varepsilon k} g_{kt_s} \leq 1 \qquad (3.2.4)$$

where k' - a subset of population, is equal to the number of projects that can be constructed at a site. This forms mutually exclusive project constraint. Only one of k' projects can be constructed at a site. For example, at a dam site if three heights of dam are possible, then k' takes values 1 to 3. The programme selects only one or none of these k' projects.

c) $\sum_{t_s=1}^{T} g_{kt_s} \leq 1$ (for $k = m+n+1, m+n+2, \ldots, M+N$) (3.2.5)

i.e., the project k can be built in the time horizon in one of the years only, if at all it can be built.

d) Contingent projects

$$g_{\overline{X}t_s} \leq g_{Yt_s} \tag{3.2.6}$$

i.e., the project $\overline{X}$ is added to the system only if project Y is added (Weingartner, 1967).

e) Compound projects

$$2g_{\overline{X}t_s} \leq g_{Yt_s} + g_{Zt_s} \tag{3.2.7}$$

Since the value of g is either zero or one, this constraint implies that adoption of project $\overline{X}$ is possible only if the projects Y and Z are included (Weingartner, 1967).

3) Demand Constraints

a) $X_{kt} \geq D_{kt}$ $k = 1,2,\ldots,$ $t = 1,2$ (3.2.8)

where index t is related to t_s by t = remainder of $\frac{t_s}{2}$ for $\frac{t_s}{2} \neq 0$

t = 2 otherwise.

D_{kt} is the sum of irrigation, power and municipal and industrial and minimum release demands and X_{kt} is the release.

b) $\sum_k \sum_t X_{kt} \leq \sum_k \sum_t R_{kt}$ (3.2.9)

For the entire basin total release must be less than the total available water in the basin for season.

4) Physical constraints

a) Minimum storage constraint

$$S_{kt} \geq S_{kt}^{min} \qquad t = 1,2 \qquad k = 1,2\ldots M \tag{3.2.10}$$

b) Maximum storage constraint

$$S_{kt} \leq V_k \qquad k = 1,2\ldots M \qquad t = 1,2 \tag{3.2.11}$$

c) Continuity equation

$$S_{kt} = S_{kt-1} + R_{kt} - X_{kt} \quad \text{for } k = 1,2,\ldots M \quad t = 1,2 \tag{3.2.12}$$

d) Canal constraints

$$L_m \leq x_{mt} \leq H_m \quad \text{for } t = 1,2 \quad m = 1,2\ldots\text{Arcs} \tag{3.2.13}$$

e) $\sum_j x_{ij} - \sum_j X_{ji} = 0$ for all i (3.2.14)

5) Returns A_{kt} can be given by the equation

$$A_{kt} = \sum_{t=1}^{2} \omega_i I_{kt} + \omega_p P_{kt} + \omega_w W_{kt} \tag{3.2.15}$$

6) $g_{kt_s} = 0 \text{ or } 1$ (3.2.16)

and all other variables are non-negative.

where

t = time index $t = 1$ - Kharif season

$= 2$ - Rabi season

t_s = time index ($t_s = 1, 2, \ldots T$) years

index t is related to t_s by

t = remainder of $t_s/2$ for $t_s/2 \neq 0$

$= 2$ otherwise

T = time horizon - years

k = project index ($k = 1, 2, \ldots m+n+1, \ldots M+N$)

m = number of existing surface reservoir projects, if any

n = number of existing well-field-units, if any

M = total number of surface reservoirs in the basin

N = total number of well-field-units in the basin

$M-m$ = number of new surface reservoirs in the basin

$N-n$ = number of new well-field-units in the basin

λ_{t_s} = discount factor

$= \frac{1}{(1+r)^{t_s}}$

r = discount rate

A_{kt_s} = returns from project k in period t_s

g_{kt_s} = decision variable

= 1 if project k is introduced in period t_s

= 0 otherwise

C_{kt_s} = capital cost of project k in period t_s

O_{kt_s} = operation, maintenance and replacement costs of project k in year t_s

X_{kt} = release from project k in period t

S_{kt} = storage of reservoir k in period t

R_{kt} = inflow to reservoir k in period t

D_{kt} = demand for water at project k in period t (sum of irrigation demand, power demand, municipal and industrial demand and down stream requirements)

S_{kt}^{min} = minimum storage in reservoir k in period t

V_k = maximum storage capacity of reservoir k

x_{ij} = flow in the arc a_{ij}

I_{kt} = irrigation supply from project k in period t

P_{kt} = water supply for power from project k in period t

W_{kt} = Municipal and industrial water supply from project k in period t

ω_i = return for unit of water (/ Hect-m) supplied to irrigation

ω_p = return for unit of water supplied for power

ω_w = return for unit of water supplied for municipal and industrial supply

a_{ij} = arc connecting nodes i and j.

3.3 Stochastic Approach

In the analysis of water resources problem some estimate of hydrological, social, technical and economic parameters is required. In the previous section - in deterministic model - all the inputs and demands are taken to be known with certainty. But these hydrological, economic and other parameters are stochastic in nature. Loucks (1969) defined uncertain event as an event in which even the probabilities of various probable outcomes are unknown, and risky events as those events for which the probabilities are known or can be estimated from the past outcomes. Though the demands are also random in nature the planners of water resources systems have substantial control over the outflows. In general outflows can be controlled by choosing appropriate types of demand. Therefore, the programming technique used in the present analysis incorporates the stochastic nature of inflows only.

3.3.1 Mathematical programming under uncertainty

There are various methods of dealing with uncertainty. These methods are:

i) sensitivity analysis or parametric programming

ii) chance constrained approach

iii) two-stage programming under uncertainty

iv) expected value approach

v) minimization of variance approach.

The choice of which approach to use depends upon the number of factors in the model and computational difficulties encountered. The chance constraint method is adopted in the present study for the following reasons:

i) By chance constraint method, the stochastic model will be reduced to an equivalent deterministic model.

ii) Near optimal deterministic models are more easily derived.

iii) The concept of risk involved is familiar to water resources planners and do not require a sharp break with the traditional approaches.

The formulation of this approach as given by Charnes, Cooper and Symonds (1959) can be stated as

$$\text{Max} \quad f\,(C'X) \tag{3.3.1}$$

Subject to $\quad P\,(AX \leq b) \geq \alpha \quad$ (3.3.2)

where X = decision variable

C = return coefficients (C′ = transpose)

b = resource value

P = probability

α = vector of probability.

In general the decision variables X are selected by a rule depending on stochastic variables A, b, and C. Thus $X = f(A,b,C)$ and the form of 'f' is often specified in advance - say linear.

The linear decision rule (L.D.R.) is used to formulate the water resources system management and design problems as a chance

constrained linear programming problem. Revelle et al., (1969) used L.D.R. for a single reservoir management model. This model was extended to a four reservoir system by Nayak and Arora (1971).

3.3.2 Linear decision rule (L.D.R.)

The simplest form of linear decision rule applied to water resources system is

$$X_{kt} = S_{kt-1} - b_{kt} \tag{3.3.3}$$

where X_{kt} is the release from reservoir k during the period t, S_{kt-1} is the storage in reservoir k at the end of period t-1 and b_{kt} is a decision variable. Equation (3.3.3) states that the discharge X_{kt} is a function of the storage at the end of the previous season since b_{kt} is constant. The discharge, however, is not a constant for a given season because the storage at the end of the previous season varies.

The b_{kt} have the following characteristics:

i) The release varies inversely with b_{kt}. In general large b_{kt} implies a small release.

ii) Negative b_{kt} are allowed; this situation however implies that a minimum natural inflow during the season is needed to meet the commitment, since the storage S_{kt-1} is not sufficient to insure the release X_{kt}.

iii) A negative b_{kt} does not necessarily imply on empty reservoir at the end of the season; if indeed the natural inflow to the reservoir were larger than the minimum inflow required to satisfy the release X_{kt}, a surplus would be generated and stored in the reservoir.

The system of reservoirs in any basin can be divided into two groups, i) independent reservoirs, and ii) dependent reservoirs. In case of independent reservoir generally there will not be any reservoirs on the stream upstream of it. The inflows to the reservoir is only natural flows. In case of dependent reservoirs the inflows consist of natural inflows plus certain portion of releases from upstream reservoirs (fig. 3.1). The linear decision rule for each type of reservoir is derived in the following sections.

3.3.3 LDR for independent reservoirs

In the case of independent reservoir (fig. 3.1) inflows to the reservoir are only the natural inflows, the 'net initial' storage is equal to their initial storage itself. The continuity equation for independent reservoirs is, therefore,

$$S_{\Omega t} = S_{\Omega t-1} + R_{\Omega t} - X_{\Omega t} \tag{3.3.4}$$

and LDR is

$$X_{\Omega t} = S_{\Omega t-1} - b_{\Omega t} \tag{3.3.5}$$

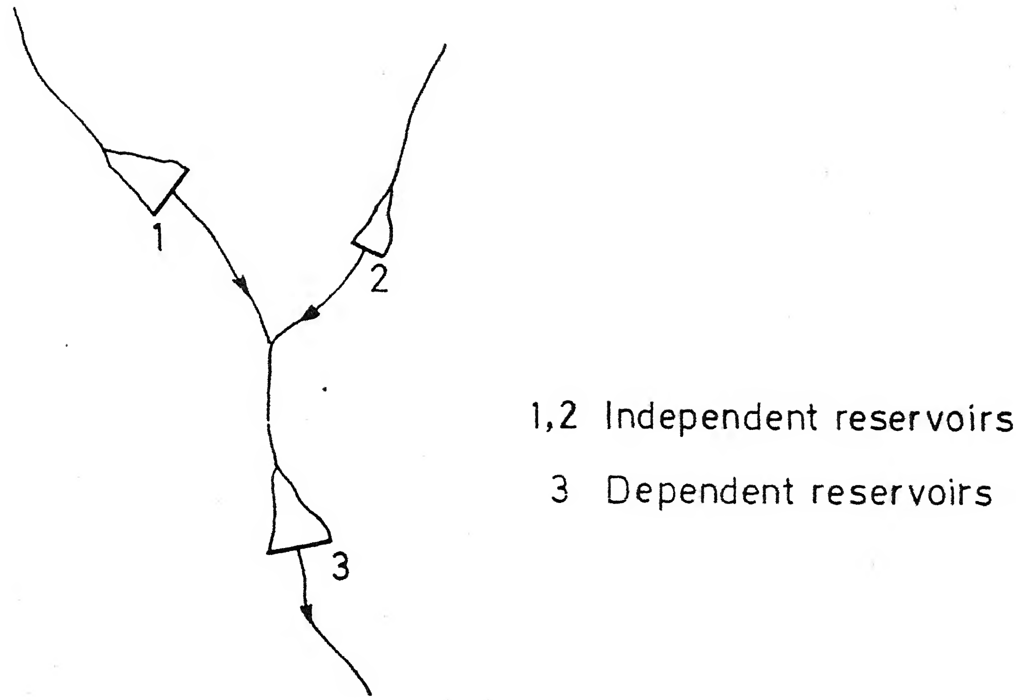


FIG.3.1 SCHEMATIC SKETCH OF INDEPENDENT AND DEPENDENT RESERVOIRS

S_{Qt} = storage in independent reservoir Q in period t

R_{Qt} = inflow to reservoir Q in period t

S_{Qt} = release from reservoir Q in period t

b_{Qt} = decision variable of reservoir Q in period t.

From equations (3.3.4) and (3.3.5) it is obtained that

$$S_{Qt} = R_{Qt} + b_{Qt} \tag{3.3.6}$$

Similarly for time period (t-1),

$$S_{Qt-1} = R_{Qt-1} + b_{Qt-1} \tag{3.3.7}$$

From equations (3.3.5) and (3.3.7) the expression for X_{Qt} will be

$$S_{Qt} = R_{Qt-1} + b_{Qt-1} - b_{Qt} \tag{3.3.8}$$

3.3.4 LDR for dependent reservoirs

The 'net initial storage' in this reservoir is

$$S_{Rt-1} + \sum_{Q \in k_{up}} R'_{Qt} \tag{3.3.9}$$

where S_{Rt-1} = storage in dependent reservoir at the end of t-1

R'_{Qt} = fraction of the release X_{Qt} from upstream reservoirs k_{up} that enters the reservoir R.

LDR is

$$X_{Rt} = S_{Rt-1} + \sum_{Q \in k_{up}} R'_{Qt} - b_{Rt} \tag{3.3.10}$$

Continuity equation

$$S_{Rt} = S_{Rt-1} + \sum_{Q \in k_{up}} R'_{Qt} + R_{Rt} - X_{Rt} \tag{3.3.11}$$

where R_{Rt} = natural flow into reservoir R in period t

X_{Rt} = release from reservoir R in period t

From equations (3.3.10) and (3.3.11) the expression for S_{Rt}

$$S_{Rt} = R_{Rt} + b_{Rt} \tag{3.3.12}$$

For time period (t-1),

$$S_{Rt-1} = R_{Rt-1} + b_{Rt-1} \tag{3.3.13}$$

From equation (3.3.10) and (3.3.11) we get,

$$X_{Rt} = R_{Rt} + b_{Rt-1} + \sum_{\Omega \varepsilon k_{up}} R'_{\Omega t} - b_{Rt} \tag{3.3.14}$$

But $R'_{\Omega t} = \psi_{\Omega t}\, X_{\Omega t}; \quad 0 \leq \psi_{\Omega t} \leq 1$ (3.3.15)

where ψ = fraction of release that becomes stream flow.

$$X_{Rt} = R_{Rt-1} + b_{Rt-1} + \sum_{\Omega \varepsilon k_{up}} \psi_{\Omega t}\, X_{\Omega t} - b_{Rt} \tag{3.3.16}$$

From equation (3.3.8)

$$X_{\Omega t} = R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t}$$

$$X_{Rt} = R_{Rt-1} + b_{Rt-1} + \sum_{\Omega \varepsilon k_{up}} \psi_{\Omega t}\,(R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t}) - b_{Rt} \tag{3.3.17}$$

On simplifying we get,

$$X_{Rt} = R_{Rt-1} + \sum_{\Omega \varepsilon k_{up}} \psi_{\Omega t}\, R_{\Omega t} + b_{Rt-1} - b_{Rt} + \sum_{\Omega \varepsilon k_{up}} \psi_{\Omega t}(b_{\Omega t-1} - b_{\Omega t}) \tag{3.3.18}$$

Summarising

for independent reservoirs

$$S_{Qt} = R_{Qt} + b_{Qt} \qquad (3.3.6)$$

$$X_{Qt} = R_{Qt-1} + b_{Qt-1} - b_{Qt} \qquad (3.3.8)$$

for dependent reservoirs

$$S_{Rt} = R_{Rt} + b_{Rt} \qquad (3.3.12)$$

$$X_{Rt} = R_{Rt-1} + b_{Rt-1} - b_{Rt} + \sum_{\Omega \varepsilon k_{up}} \psi_{Qt} \left(R_{Qt-1} + b_{Qt-1} - b_{Qt}\right) \qquad (3.3.18)$$

3.4 Stochastic Model

Objective function

Maximize Z where

$$Z = \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{k=1}^{m+n} A_{kt_s} + \sum_{t_s=1}^{T} \lambda_{t_s} \sum_{k=m+n+1}^{M+N} g_{kt_s} A_{kt_s}$$

$$- \sum_{t=1}^{T} \lambda_{t_s} \sum_{k=m+n+1}^{M+N} g_{kt_s} C_{kt_s} - \sum_{t=1}^{T} \lambda_{t_s} \sum_{k=1}^{m+n} O_{kt_s}$$

$$- \sum_{t=1}^{T} \lambda_{kt_s} \sum_{k=m+n+1}^{M+N} O_{kt_s} \qquad (3.4.1)$$

The budgetary, institutional constraints remain unchanged since they contain no stochastic variables. (It is conceivable that the outlay in a year could be stochastic; however, such contingencies are not considered here.)

These constraints are:

1) Budgetary constraints

$$\sum_{k=m+n+1}^{M+N} g_{kt_s} C_{kt_s} \leq M_{t_s} \quad \text{for all } t_s \tag{3.4.2}$$

2) Institutional constraints

i) $$\sum_{k=m+n+1}^{M+N} g_{kt_s} \leq b \quad \text{for all } t_s \tag{3.4.3}$$

ii) $$\sum_{t_s=1}^{T} \sum_{k\varepsilon k'} g_{kt_s} = 1 \tag{3.4.4}$$

iii) $$\sum_{t_s=1}^{T} g_{kt_s} \leq 1 \quad \text{for } k = m+n+1, \ldots M+N \tag{3.4.5}$$

iv) $$g_{Xt_s} \leq g_{Yt_s} \quad \text{for all } t_s \tag{3.4.6}$$

v) $$2g_{Xt_s} \leq g_{Yt_s} + g_{Zt_s} \quad \text{for all } t_s \tag{3.4.7}$$

3) Maximum storage constraints

$$S_{kt} \leq V_{kt} \quad \text{for all } k \text{ and } t \tag{3.4.8}$$

4) Canal constraints

i) $$L_m \leq x_{tm} \leq H_m \quad \text{for all } t \text{ and } m \tag{3.4.9}$$

ii) $$\sum_j x_{ij} - \sum_j x_{ji} = 0 \text{ for all } i \tag{3.4.10}$$

5) Demand constraint

To provide water for different purposes, the release commitment X_{kt} should exceed the demand with reliability say γ_1. In

probability notation this constraint is

$$P\ (X_{kt} \geq D_{kt}) \geq \gamma_1 \tag{3.4.11}$$

Similarly for the minimum storage constraint

$$P\ (S_{kt} \geq S_{kt}^{min}) \geq \gamma_2 \tag{3.4.12}$$

where γ_2 is again reliability.

By using LDR these two constraints (3.4.11) and (3.4.12) are converted into equivalent deterministic constraints.

3.4.1 Minimum release constraint

Substituting (3.3.8) into (3.4.11) the release constraint for independent reservoir becomes,

$$P\left(R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t} \geq D_{\Omega t}\right) \geq \gamma_1 \tag{3.4.13}$$

$$P\left(R_{\Omega t-1} \geq D_{\Omega t} + b_{\Omega t} - b_{\Omega t-1}\right) \geq \gamma_1$$

$$1 - F_R\ (D_{\Omega t} + b_{\Omega t} - b_{\Omega t-1}) \geq \gamma_1$$

$$F_R\ (D_{\Omega t} + b_{\Omega t} - b_{\Omega t-1}) \leq (1 - \gamma_1)$$

or $$D_{\Omega t} + b_{\Omega t} - b_{\Omega t-1} \leq F^{-1}\ (1 - \gamma_1) \tag{3.4.14}$$

Substituting (3.3.18) into (3.4.11), the release constraint for dependent reservoir becomes

$$P\ \{R_{Rt-1} + b_{Rt-1} - b_{Rt} + \sum_{\Omega \varepsilon K_{up}} \psi_{\Omega t}\ (R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t}) \geq D_{Rt}\} \geq \gamma_1 \tag{3.4.15}$$

i.e., $$P\{R_{Rt-1} \geq D_{Rt} + b_{Rt} - b_{Rt-1} - \sum_{\Omega \epsilon k_{up}} \psi_{\Omega t} (R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t})\} \geq \gamma_1$$

$$1 - F_R (D_{Rt} + b_{Rt} + b_{Rt-1} - \sum_{\Omega \epsilon k_{up}} \psi_{\Omega t} (R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t})) \geq \gamma_1$$

$$F_R \{D_{Rt} + b_{Rt} - b_{Rt-1} - \sum_{\Omega \epsilon k_{up}} \psi_{\Omega t} (R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t})\} \leq (1 - \gamma_1)$$

$$D_{Rt} + b_{Rt} - b_{Rt-1} - \sum_{\Omega \epsilon k_{up}} \psi_{\Omega t} (R_{\Omega t-1} + b_{\Omega t-1} - b_{\Omega t}) \leq F^{-1}(1-\gamma_1) \tag{3.4.16}$$

3.4.2 Minimum storage constraint

Substituting (3.3.6) into (3.4.12) the minimum storage constraint for independent reservoir

$$P\ (R_{\Omega t} + b_{\Omega t} \geq S_{\Omega t}^{min}) \geq \gamma_2 \tag{3.4.17}$$

$$P\ (R_{\Omega t} \geq S_{\Omega t}^{min} - b_{\Omega t}) \geq \gamma_2$$

$$1 - F_\Omega\ (S_{\Omega t}^{min} - b_{\Omega t}) \geq \gamma_2$$

$$S_{\Omega t}^{min} - b_{\Omega t} \leq F^{-1}\ (1 - \gamma_2) \tag{3.4.18}$$

Similarly for dependent reservoir the minimum storage constraint, from (3.3.12) and (3.4.12) will be

$$P\ (R_{Rt} + b_{Rt} \geq S_{Rt}^{min}) \geq \gamma_2 \tag{3.4.19}$$

$$S_{Rt}^{min} - b_{Rt} \leq F^{-1}\ (1 - \gamma_2) \tag{3.4.20}$$

where $F^{-1}(r)$ is a solution of

$$F(r) = P(R \leq r) = \gamma \tag{3.4.21}$$

$F^{-1}(r)$ is a known quantity that can be obtained from the cumulative distribution function of inflows.

Thus the chance constraints are replaced by the equivalent deterministic constraints.

3.5 Chance Constraint Formulation with Evaporation Losses

In arid and semi-arid regions, evaporation losses play important role in planning and designing of water resources systems. Generally the evaporation losses are expressed as percentage of storage in any time period. In the present analysis the expression of the type $E_{kt} = \delta_{kt}\ (S_{kt} + S_{kt-1})$ is used (Chow & Windsor, 1972), where E_{kt} is the evaporation losses in period t for reservoir k, and δ_{kt} is evaporation coefficient. As Harbeck (1966) suggested the depth of evaporation loss in any season is relatively constant from year to year, i.e., the value of δ_{kt} remains constant from year to year. The evaporation losses can be expressed as a linear function of surface area. But at any specific reservoir site there is a definite relationship between surface area and storage volume. Hence the evaporation loss expression is expressed as storage volume and approximated by a straight line with positive slope.

In the present analysis, a projected storage based on the actual storage at the beginning of the period and on the anticipated

evaporation loss during the period is taken for formulation of the model. The expression for evaporation losses is

$$E_{kt} = \delta_{kt} \, (S_{kt} + S_{kt-1}) \tag{3.5.1}$$

The linear decision rule can be expressed as

$$X_{kt} = \bar{S}_{kt-1} - b_{kt} \tag{3.5.2}$$

where $\bar{S}_{kt-1}$ is projected storage taking evaporation into consideration. For the linear decision rule to be an effective computational device, $\bar{S}_{kt-1}$ is expressed as a function of the storage (Revelle & Kirby, 1970).

$$\bar{S}_{kt-1} = \eta_{kt} \, S_{kt-1} \tag{3.5.3}$$

where $\eta_{kt} = 1 - \delta_{kt}$ (3.5.4)

The continuity equation for the reservoir is

$$S_{kt} = S_{kt-1} + R_{kt} - X_{kt} - E_{kt} \tag{3.5.5}$$

Substituting (3.5.1) and (3.5.2) into (3.5.5) we get

$$S_{kt} = \frac{R_{kt} + b_{kt}}{1 + \delta_{kt}} \tag{3.5.6}$$

$$= (R_{kt} - b_{kt}) \, \theta_{kt}^{-1} \tag{3.5.7}$$

where $\theta_{kt} = 1 + \delta_{kt}$ (3.5.8)

Similarly, $S_{kt-1} = (R_{kt-1} + b_{kt-1}) \, \theta_{kt-1}^{-1}$ (3.5.9)

and from (3.5.3) and (3.5.9)

$$\bar{S}_{kt-1} = \eta_{kt} \{ R_{kt-1} + b_{kt-1} \} \, \theta_{t-1}^{-1} \tag{3.5.10}$$

$$X_{kt} = \frac{\eta_{kt}}{\theta_{kt-1}} \{R_{kt-1} + b_{kt-1}\} - b_{kt} \tag{3.5.11}$$

3.6 Model with Evaporation Losses

The objective function (3.4.1) and constraints (3.4.2)-(3.4.10) remain the same. The minimum release constraint and minimum storage constraints become:

Minimum release constraint

$$P\ (X_{kt} \geq D_{kt}) \geq \gamma_1 \tag{3.6.1}$$

Substituting for X_{kt} from (3.5.11)

$$P\{\frac{\eta_{kt}}{\theta_{kt-1}}\ (R_{kt-1} + b_{kt-1}) - b_{kt} \geq D_{kt}\} \geq \gamma_1 \tag{3.6.2}$$

$$P\{R_{kt-1} + b_{kt-1} \geq (D_{kt} + b_{kt})\ \frac{\theta_{kt-1}}{\eta_{kt}}\} \geq \gamma_1$$

$$P\{R_{kt-1} \geq (D_{kt} + b_{kt})\ \frac{\theta_{kt-1}}{\eta_{kt}} - b_{kt-1}\} \geq \gamma_1$$

$$F_R\ \ (D_{kt} + b_{kt})\ \frac{\theta_{kt-1}}{\eta_{kt}} - b_{kt-1} \leq (1 - \gamma_1)$$

$$(D_{kt} + b_{kt})\ \frac{\theta_{kt-1}}{\eta_{kt}} - b_{kt-1} \leq F^{-1}\ (1 - \gamma_1) \tag{3.6.3}$$

Minimum storage constraint

$$P\ (S_{kt} \geq S_{kt}^{min}) \geq \gamma_2 \tag{3.6.4}$$

Substituting for S_{kt} from (3.5.6) & (3.6.4) the following expressions are obtained;

$$P\{(R_{kt} + b_{kt})\,\theta_{kt}^{-1} \geq S_{kt}^{min}\} \geq \gamma_2$$

$$P\{R_{kt} \geq S_{kt}^{min}\,\theta_{kt} - b_{kt}\} \geq \gamma_2$$

$$F\{S_{kt}^{min}\,\theta_{kt} - b_{kt}\} \leq (1 - \gamma_2)$$

$$S_{kt}^{min}\,\theta_{kt} - b_{kt} \leq F^{-1}\,(1 - \gamma_2) \tag{3.6.5}$$

The subscripts in these expressions are suitably modified for independent and dependent reservoirs as explained earlier in section 3.4. That is, for independent reservoirs the subscript k should be replaced by Q, and for dependent reservoirs it should be replaced by R.

Chapter 4

METHODOLOGY

BRANCH AND BOUND AND OUT-OF-KILTER ALGORITHMS

4.1 Introduction

The methods generally employed in water resources systems analysis are mathematical programming methods and simulation techniques. Simulation is a process that duplicates the essence of a system without attaining reality itself (Tocher, 1963). A system is modelled either on analog or digital or on both. The response of the system to any input data can be predicted. However, the simulation model is not self-optimizing. Simulation is an excellent tool in modelling complex systems but has less utility where the number of variables are large as in case of water resources systems. Mathematical programming methods are self-optimizing. There are many programming methods which are used in the water resources systems analysis.

In Chapter 3, the water resources system model is developed as a combination of investment policy problem and operating policy problem which are solved iteratively.

The problem is of zero-one (0-1) mixed integer programming type where the system elements are either selected or rejected and operation policy giving the releases to meet the various demands is obtained. Consequently, all the feasible solutions contain a mixture of integer and continuous variables, and integer variables are restricted to the values zero or one. In solving the model it is required to find (i) which of the projects should be built, at what time and to what scale, and (ii) the amount of releases such that the objective function is maximized.

Mixed integer programming method requires that the objective function be separable with respect to integer and continuous variables, i.e., the two sets of variables must be capable of being linearly summed (Hadley, 1964). But in the model presented in Chapter 3 there is an interaction between the variables in the objective function and also in some of the constraints. Therefore, a new method of approach is sought for solving the model.

The problem is decomposed into two units as a combinatorial problem (a) investment problem, and (b) operation policy problem. The investment problem is solved by branch and bound technique. The operation policy problem is solved by net-work analysis using Fulkerson's out-of-Kilter algorithm. The connection between these two problems is due to the fact that the investment policy problem is solved by obtaining optimal solution of operating

policy problem and the operating policy problem is dependent on the number of projects obtained by the investment policy problem (Figure 4.1).

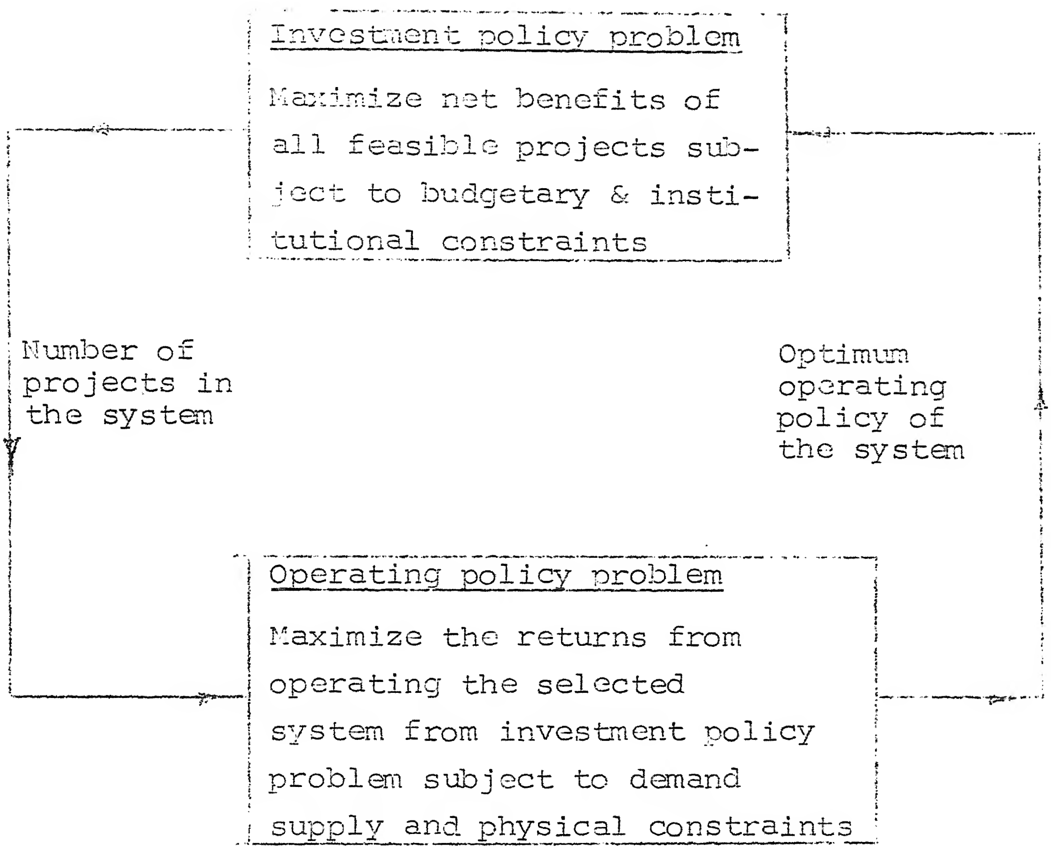


Fig. 4.1 - Connection between Investment policy and Operating policy problems.

4.2 Investment Policy Problem

This problem falls into a category of integer programming methods with variables taking only two values, either zero or one.

The problem is solved by branch & bound technique (Little et al., 1963). Branch and bound is a tree searching technique. The common features of this technique are:

(1) They are easy to understand,

(2) They are better suited for computer application than cutting plane techniques.

Branch and bound technique is structured as a search technique in the space of feasible solutions. The feasible solution space is repeatedly partitioned into smaller and smaller sub-sets, and the bound is calculated for each sub-set. After each partitioning, those sub-sets with a bound less than that of the known feasible solution are excluded from further partitioning. The partitioning continues till the feasible solution is found such that its return is greater than the returns of any sub-set.

For zero-one integer programming with p variables there are 2^p solutions. These 2^p solutions are partitioned into n+1 sub-sets. The s^{th} sub-set (s = 0,1,2....n) contains all solutions with s variables being 1 and (p-s) variables being zero. The zeroth sub-set contains one solution $y_j=0$ (J = 1,2,3,...p). The first sub-set contains $\binom{p}{1}$ solutions: $y_1=1$ and $y_j=0$, $(j\neq 1)$; $y_2=1$, $y_j=0$, $(j\neq 2)$; and so on. In general, s^{th} sub-set has $\binom{p}{s}$ solutions. In testing the feasibility of solutions, the values of variables y_j are substituted into the constraint set directly.

The process starts with the highest node; and then follows an intermediate successor to the highest node. A node is said to be a terminating node if any of its successors nodes are not tested.

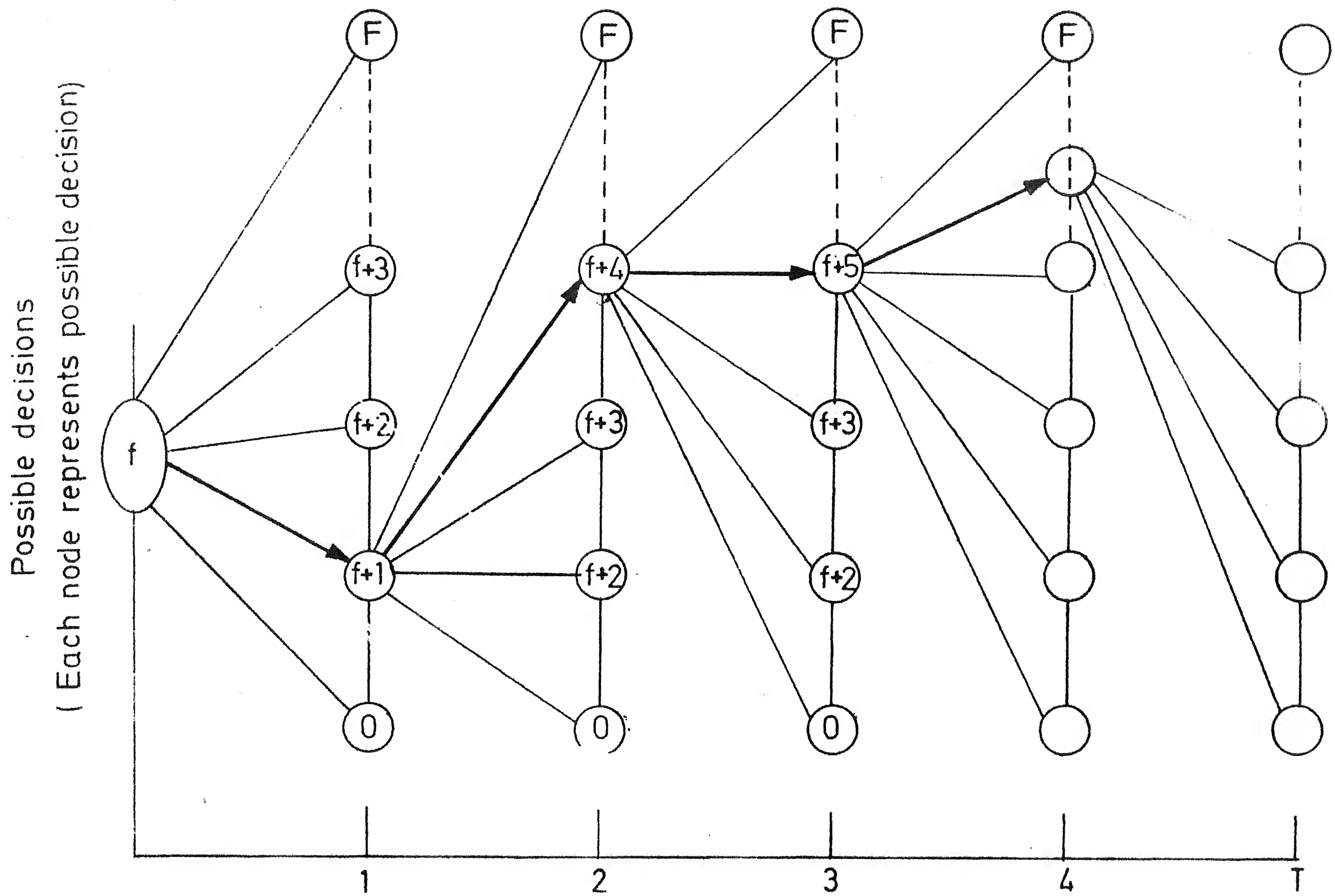
The investment policy problem is represented as in Figure 4.2.

The operation policy problem is solved for the original system as well as the system with addition of a project in any year t. If, and only if, the solution of latter operation policy problem gives a higher return than the operation policy of former problem, the new project is selected in the year t. The procedure is repeated for each subsequent year. The termination of branching occurs at T (time-horizon) or when all the projects have been introduced into the system. The optimal solution is found when all the feasible nodes have been searched.

4.3 Operation Policy Problem

From the investment policy, if it is decided to introduce a new project into the system at the beginning of year t, its feasibility will be tested with respect to its operational policy. The operation policy problem is solved as a net-work problem. Fulkersons out-of-Kilter algorithm is used in the analysis. The following gives a brief description of the method.

A net-work consists of a set of nodes and a set of arcs connecting the nodes, Figure 4.3.



→ Time in years

f m+n Existing

F Total number of

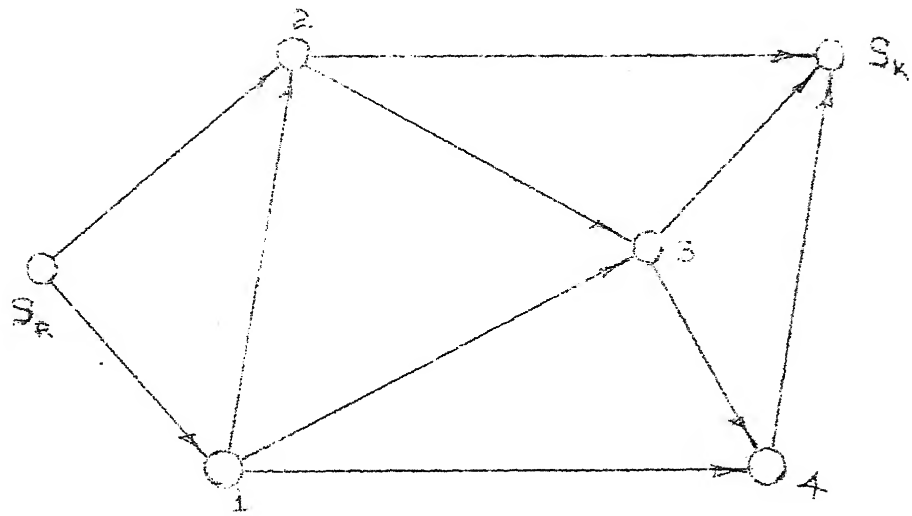


Fig. 4.3 - A typical net-work

If the arc has a direction then it is called a directed arc. In water resources systems the directed net-work analysis is used. There are two special nodes in the net-work, namely, S_R (source) and S_k (sink). Let S_i and S_j be the nodes and a_{ij} be the arc joining S_i to S_j. The sequence of nodes and arcs S_R, a_{R1}, S_1, a_{12}, S_2 ..., S_k is called a chain leading from S_R to S_k. If S_R coincides with S_k, then it is called a directed cycle. Associated with each arc there is an upper flow capacity H_{ij} and a low flow capacity L_{ij} and also the return b_{ij} from passing

one unit of water through the arc. Let the flow in the arc a_{ij} be x_{ij}. Then the problem is to find the values of x_{ij} such that the returns will be maximum without violating the constraints.

Maximize $\overline{Z}$

where $$\overline{Z} = \sum_i \sum_j b_{ij} x_{ij} \tag{4.3.1}$$

Subject to $$x_{ij} \leq H_{ij} \text{ for each } a_{ij} \tag{4.3.2}$$

$$-x_{ij} \leq -L_{ij} \text{ for each } a_{ij} \tag{4.3.3}$$

$$\sum_j x_{ij} - \sum_j x_{ji} = 0 \text{ for each } i \tag{4.3.4}$$

$$x_{ij} \geq 0 \text{ for each } a_{ij} \tag{4.3.4}$$

From duality theory, there is a dual variable associated with each primal constraint and a dual constraint associated with each primal variable. Let σ_i denote the dual variable associated with the i^{th} primal conservation of flow equation (4.3.4). Let y_{ij} denote the dual variable corresponding to upper bound constraint (4.3.2) and Z_{ij} be the dual variable associated with lower bound constraint (4.3.3).

The dual problem can be stated as optimize Z' where

$$Z' = \sum_i \sum_j H_{ij} y_{ij} - \sum_i \sum_j L_{ij} Z_{ij} \text{ over all arcs} \tag{4.3.6}$$

Subject to

$$\sigma_i - \sigma_j + y_{ij} - z_{ij} \geq b_{ij} \text{ for all } i,j \tag{4.3.7}$$

$$y_{ij} \geq 0$$
$$z_{ij} \geq 0 \quad \text{for all } i \,\&\, j \qquad (4.3.8)$$

and the σ variables are unrestricted in sign since these dual variables are associated with quality constraints in the primal problem.

At the optimal value, the value of primal and dual objective functions are equal ($\overline{Z} = Z'$). The relationship between the primal and dual variables is known as complimentary slackness conditions (Hadley, 1964). These conditions are

$$\text{if} \quad y_{ij} > 0, \text{ it follows that } x_{ij} = H_{ij} \qquad (4.3.9)$$

$$\text{if} \quad z_{ij} > 0, \text{ it follows that } x_{ij} = L_{ij} \qquad (4.3.10)$$

$$\text{and if} \quad \sigma_i - \sigma_j + y_{ij} - z_{ij} = b_{ij}, \text{ it follows that } L_{ij} \leq x_{ij} \leq H_{ij} \qquad (4.3.11)$$

Fulkerson (1961) developed the out-of-Kilter algorithm (O.K.A.) which takes the advantage of above relationship and examines a relatively small sub-set of the dual variables in a search to get optimal value of the objective function. The efficiency is achieved by defining the quantities,

$$C_{ij} = \sigma_i - \sigma_j - b_{ij} \qquad (4.3.12)$$

$$y_{ij} = \text{Max } (0, -C_{ij}) \qquad (4.3.13)$$

$$Z_{ij} = \text{Max } (0, C_{ij}) \qquad (4.3.14)$$

such that y_{ij} and z_{ij} satisfy (4.3.7) and (4.3.8). With these definitions, the complementary slackness conditions may be written in the following form,

$$\text{if } C_{ij} < 0, \quad x_{ij} = H_{ij} \tag{4.3.15}$$

$$\text{if } C_{ij} > 0, \quad x_{ij} = L_{ij} \tag{4.3.16}$$

$$\text{and if } C_{ij} = 0, \quad L_{ij} \leq x_{ij} \leq H_{ij} \tag{4.3.17}$$

These three conditions along with continuity equation condition (4.3.4) determine the sufficient conditions of optimality.

Those arcs which do not satisfy at least one of the above conditions are known as out-of-Kilter arcs. The general method of solving net-work problem is given by Fulkerson (1962). The O.K.A. seeks systematically to direct the flows and assign the values to the α variables so that each arc satisfies the optimality conditions, i.e., each arc is in in-Kilter condition.

The variable α_i may be considered as the price associated with a node i and C_{ij} represents the total price of unit flow from node i to node j.

With the above optimality conditions, different states of arc stated as in the table 4.1.

labelling the nodes to indicate the direction that the flow in an arc may be increased. Once the flow augmenting path is found, the flow is increased to its maximum capacity along the path and all the labels on the nodes are erased. Then assign new labels to nodes based on new flows. Thus this algorithm consists of two steps. Step 1 is the labelling procedure and step 2 is the implementation of flow change

Step 1: Labelling Procedure

Every node is always in one of the following three states:

a) Labelled and scanned

b) Labelled and unscanned

c) Unlabelled.

A label for a node S_j always has two parts, first part is the index of node S_i from which the flow can be sent to S_j; and second part is a number which indicates the maximum amount of flow that can be sent to S_j without violating capacity constraints.

A node is labelled and scanned if it has label and all its neighbouring nodes are inspected.

A node is labelled and unscanned if it has a label and not all its neighbouring nodes have been scanned.

A node is unlabelled if it has no label.

Initially all nodes are unlabelled. Select a node S_j and assign S_j the label of the form $(i^+, \varepsilon(j))$ or $(i^-, \varepsilon(j))$ where

i^+ states that the flow can be sent from i to j and $\varepsilon(j)$ indicates the amount of flow that can be sent.

To all neighbouring nodes S_m of S_j, which are unlabeled, and for which $0 \leq x_{jm} \leq H_{jm}$, assign the label $(j^+, \varepsilon(m))$ where $\varepsilon(m)$ is equal to min $\{\varepsilon(j), H_{jm}-x_{jm}\}$ and to all neighbouring nodes S_m which are unlabelled and for which $x_{mj} > 0$, assign the label $\{j^-, \varepsilon(m)\}$ where $\varepsilon(m) = \min\{\varepsilon(j), x_{mj}\}$. The positive (+ve) and negative (-ve) signs in the label indicate, how the flow should be changed in the step two. Now with all neighbouring nodes of S_j which are scanned, S_j is considered to be labelled and scanned. All nodes S_m are now labelled and unscanned. Continue to assign labels to neighbours of labelled and unscanned nodes, until either S_k (sink node) is labelled or no more labels can be assigned, and S_k is unlabelled. If S_k cannot be labelled, no flow-augmenting paths exist and hence the flow is maximum. If S_k is labelled, a flow augmenting path can be found using step two.

Step 2:

Assume that S_k is labelled $(m^+, \varepsilon(k))$. Replace x_{mk} by $x_{mk} + \varepsilon(k)$ and turn to S_m. If S_m is labelled $(j^+, \varepsilon(m))$, replace x_{jm} by $x_{jm} + \varepsilon(m)$, and turn to S_j. If S_m is labelled $(j^-, \varepsilon(m))$, replace x_{mj} by $x_{mj} - \varepsilon(m)$, and turn to S_j. Continue this process until S_R is reached. Erase the labels on all nodes and go back to step one.

Steps one and two are iterated until the maximum flow condition is obtained. Out-of-Kilter algorithm steps are given in the flow diagram, Figure 4.4.

A computer programme is available (Himmelblau, 1973). It is basically in the original form as written by Texas-Water-Development-Board and apparently has not undergone testing on large scale problems. Several errors in the programme have been detected by the writer during this work and several subroutines are introduced to suit the present large scale river basin model.

The model is solved using IBM 7044/1401 system.

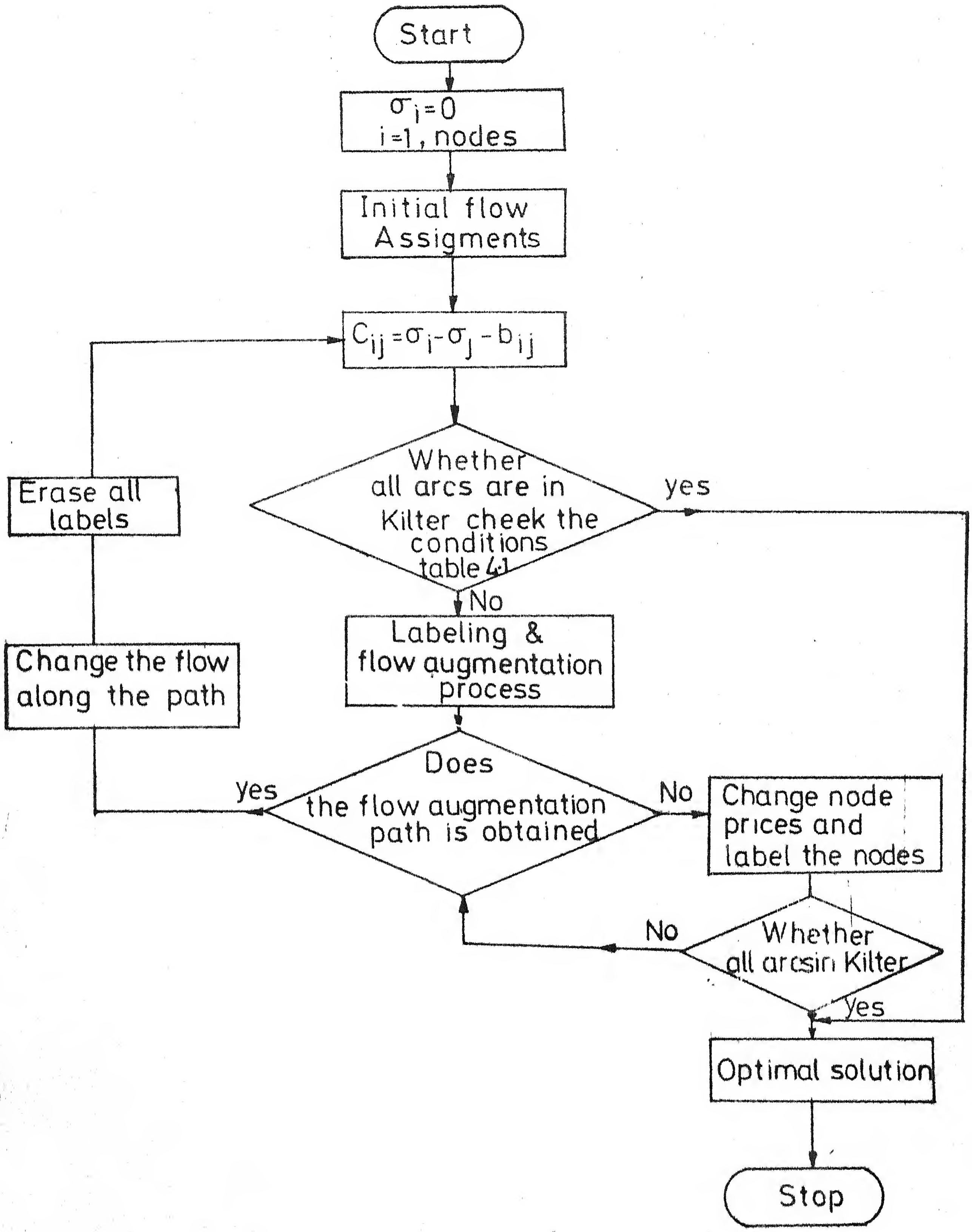


FIG.4.4 FLOW DIAGRAM FOR OUT-OF-KILTER ALGORITHM

Chapter 5

MODEL APPLICATION TO CAUVERY RIVER BASIN - (KARNATAKA*-INDIA)

5.1 Introduction

The different models presented in the Chapter 3 are applied to the development of water resources in the Cauvery basin. Economy of the region depends almost entirely upon agriculture and most of the water is required for irrigation purposes.

The physical and hydrological characteristics of study area are briefly presented first. Then the mathematical model representing hydrological, physical, economic and institutional parameters is presented and solutions are obtained.

5.2 Physical Description of the Model

The study area is that part of Cauvery basin which lies in the Karnataka state. It comprises of upstream and middle reaches of the Cauvery river (fig. 5.1)

The drainage area of the basin under study is approximately 36,000 sq.km. Entire Cauvery basin spreads between the longitudes of 75° 30'E & 79° 45°E and latitudes of $10^{\circ}5$'N & $13^{\circ}30$'N.

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*Name of the state was changed from Mysore to Karnataka, 1.11.1974.

Fig. 5.1

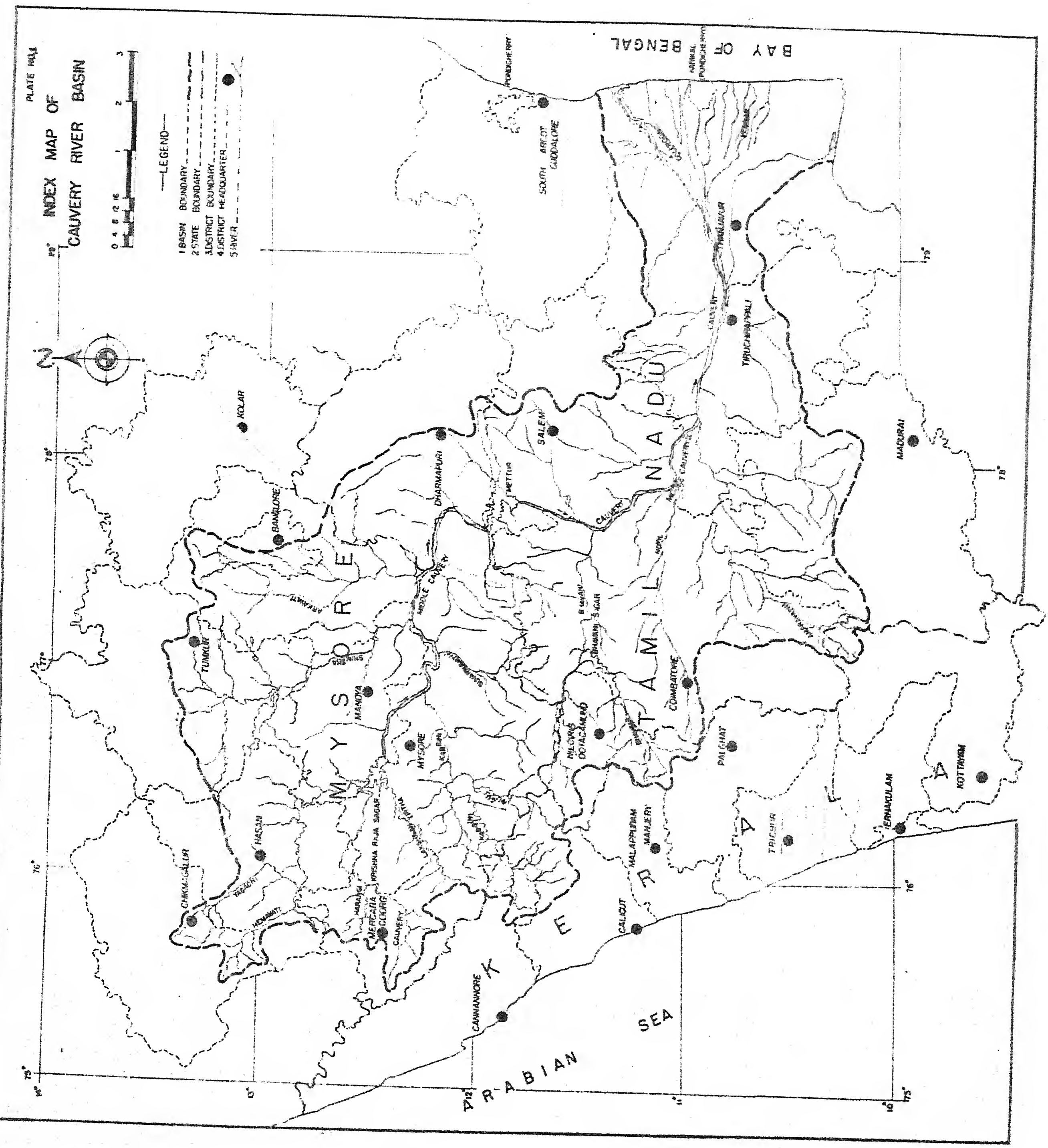


PLATE NO.1
INDEX MAP OF CAUVERY RIVER BASIN
LEGEND
1 BASIN BOUNDARY
2 STATE BOUNDARY
3 DISTRICT BOUNDARY
4 DISTRICT HEADQUARTER
5 RIVER
MYSORE
TAMIL NADU
KERALA
BAY OF BENGAL
ARABIAN SEA
KOLAR
BANGALORE
TUMKUR
HASAN
CHIKMAGALUR
MANDYA
MYSORE
MERCARA
COORG
KRISHNA RAJA SAGAR
DHARMAPURI
SALEM
METTUR
COIMBATORE
NILGIRIS OOTACAMUND
TIRUCHIRAPPALLI
THANJAVUR
MADURAI
SOUTH ARCOT CUDDALORE
PONDICHERRY
PALGHAT
TRICHUR
ERNAKULAM
KOTTAYAM
MALAPPURAM
MANJERI
CALICUT
CANNANORE
CAUVERY
MIDDLE CAUVERY
ARKAVATI
SHIMSHA
KABINI
HEMAVATI

Located in peninsular India, the basin covers the areas in the states of Karnataka, Kerala and Tamilnadu.

The state-wise distribution of drainage area is given in the table 5.1 (CFFC, 1972)

Table 5.1

Area of the State and drainage basin

State	Area of the state (sq.km.)	Area of drainage basin (sq.km.)	Remarks
Karnataka	1,91,733	36,240	Drainage basin includes western ghats area where the river rises and the plateau of Karnataka
Kerala	38,864	2,930	Drainage area consists of ghat areas
Tamil Nadu	1,30,070	48,730	Drainage basin includes middle reaches and delta area

Total area of drainage basin 87,900 sq.km.

The area that lies in Karnataka state is considered for analysis. This study area is divided physiographically into western ghats region and plateau of Karnataka. The western ghat area is mountainous and covered with thick vegetation. River Cauvery takes birth at Talakaveri in Coorg district of ghat areas (Fig. 5.1). The location where it rises is roughly

$25^{\circ}24'$N longitude and $74^{\circ}34'$E latitude at an elevation of 1341 m above M.S.L. in Bramhagiri range of hills. The river has steep banks and many ideal sites are available for impounding water.

The plateau of Karnataka with average elevation of 750 m, slopes gently towards E-NE direction.

There are a number of tributaries which join the river along its course from both sides of the river (Fig. 5.1). The important tributaries from the left side are Harangi, Hemavathy, Shimsha and Arkavathi. The tributaries which join the river from right side (south side) are Lakshmana-Theertha, Kabini, Suvarnavathy and Uduthore-halla.

The catchment area of Harangi river lies in ghat area which receives heavy rain fall by south-west monsoon (June to October). It drains an area of 540 sq. km. and joins the river Cauvery at Kudige in Coorg district.

Hemavathy river, with its tributary Yagachi, is a major tributary which joins the river from the left side. The total drainage area of this tributary is 5200 sq.km.

The other two tributaries which join the river from left are Shimsha and Arkavathi. These two rivers flow in the plateau of Karnataka- which is a rain-shadow area of the western ghats.

Lakshmana-Theertha river joins the river Cauvery from south and drains the areas in Coorg and Mysore districts.

River Kabini along with its numerous tributaries is a major river which joins Cauvery river from the south. It rises in the ghats of Kerala state and drains a total area of 6690 sq.km. both in Kerala and Karnataka states. It traverses a length of 210 km before joining the Cauvery river at Tirumakudala Narasipura, in Mysore district. There are a number of sites available on this river for conservation and control of water.

Suvarnavathy and Uduthore-halla are other two tributaries which join Cauvery from right. These two tributaries flow in Karnataka plateau region and carry moderate runoff.

The upper reaches of the basin are steep and river flows in narrow gorges. At Sreerangapatnam (d/s of the city of Mysore) the river divides into two branches and forms an island where the famous bird sanctuary Rangana-Tittu is situated. The river flows in eastwardly direction in the plains of Karnataka. At Shivasamudram a few kilometers upstream of the confluence of Shimsha, the river divides into two branches and falls through a height of more than 91 m in a series of falls and rapids. The two major falls are Gagana Chukki and Bhara Chukki. There is an hydroelectric station at this fall; and it was constructed in 1902. The two branches of river join down-stream of the falls and flow in a narrow gorge. At one reach the width of the river is so narrow, it is named Mekedatu which literally means that a goat can leap across. After this point the river flows in eastward direction and receives Arkavathi from left and Uduthore-halla from the right.

River Cauvery runs a total length of 320 km in Karnataka state and for about 64 km it forms the boundary between Karnataka and Tamil Nadu States.

5.3 Climate

The climate of the basin area under study is essentially tropical monsoon type. The year can be divided into two seasons as per agricultural practices - Kharif and Rabi seasons. Kharif season spans from month of May to month of October. It includes hot months followed by south-west monsoon period. Ghat areas and adjoining upper reaches of the basin get major portion of the rainfall in this season.

Plateau of Karnataka receives moderate rain fall during this season.

Rabi season comprises of the months of November through April. During this season north-east monsoon gives moderate to heavy rain fall in the plateau of Karnataka in the months of October and November.

The normal annual rainfall distribution is shown in Table 5.2.

Table 5.2

Rain fall distribution

Month	% of rain fall	Remarks
1	2	3
1 January	0.30	
2 February	0.40	Rabi Season
3 March	0.90	
4 April	4.50	

Table 5.2 (...Contd.)

	1	2	3
5	May	8.80	
6	June	14.60	
7	July	25.50	
8	August	16.10	Kharif season
9	September	11.90	
10	October	10.10	
11	November	5.20	Rabi season
12	December	1.00	

<u>Evaporation</u>: This is an important parameter in water resources planning and management studies. Unfortunately very little information is available about evaporation losses. However, the evaporation losses are estimated using meteorological data. The average daily evaporation losses are given in Table 5.3.

Table 5.3

Average evaporation losses

6

	Month	Average daily evaporation loss in mm	Percentage of loss
	1	2	3
1	January	5.50	7.10
2	February	7.00	8.90
3	March	7.60	9.60
4	April	7.10	9.00

Table 5.3 (...Contd.)

1		2	3
5	May	7.00	8.90
6	June	8.30	10.50
7	July	7.10	9.00
8	August	8.80	8.60
9	September	7.30	9.20
10	October	5.80	7.40
11	November	4.70	6.00
12	December	4.60	5.80

5.4 Geology and Soils of the Basin

Gneisses cover the major portion of the basin. Granite occurs as intrusions in the gneisses showing characteristic structure of plutonic rocks. The Arkavathi sub-basin contains granite formation which runs from Tumkur to Sivasamudram.

The study area is covered with red soil. The loamy structure of red soil make it suitable for growing a large variety of crops.

5.5 Crops

Rice is the widely grown irrigated crop followed by sugarcane. Other important crops are ragi, groundnut and some garden crops. Whole of arable area can be brought under irrigation with assured

supply of water. The entire basin has excellent drainage facility. Therefore, irrigation drainage presents no problem.

5.6 Water Resources

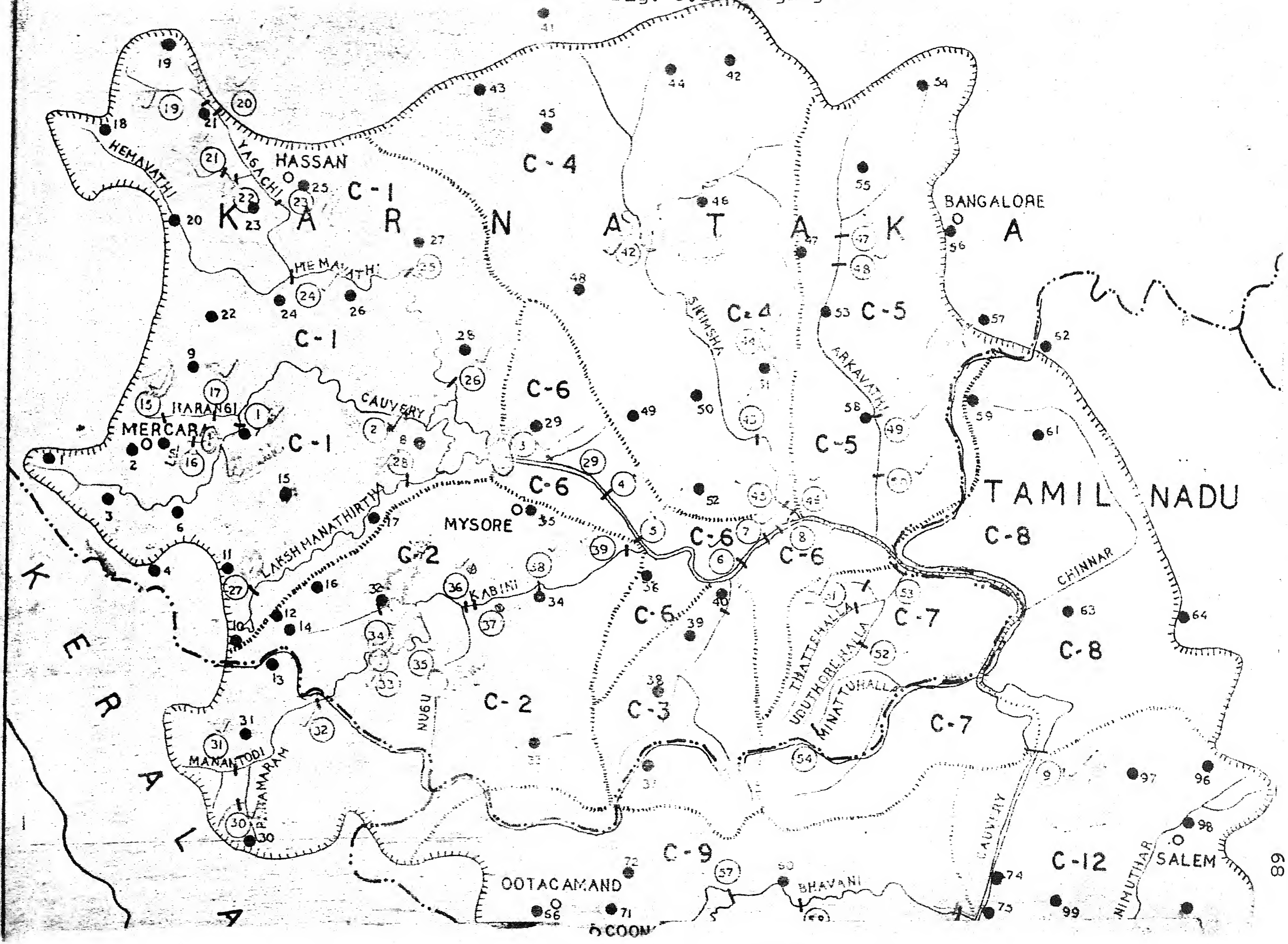
The most commonly used geographic units for water resources planning and development is the river basin or a closely related group of basins, which drain to a common point. With such a hydrologic complex the water supplies are connected. Within the major area under consideration many streams and stream systems make up the smaller hydrologic units which lead themselves to analysis as individual units. The entire Cauvery basin is divided into sixteen hydrological units. Out of these sixteen, first seven lie in the study area (Karnataka part of the basin). Table 5.4 and Figure 5.2 give the details of these study units.

Table 5.4

Details of Hydrological Units

Study unit	Area covered
C_1	Upper reaches of Cauvery, Harangi river, Hemavathy river system and Lakshmana Theertha river
C_2	Kabini river with all its tributaries
C_3	Suvarnavathy and Gundal rivers
C_4	Shimsha river system
C_5	Arkavathi river system
C_6	Area along the course of the river which is not covered by other units
C_7	Uduthore-halla basin

Fig. 5.2. Gauging stations



Discharge sites in Cauvery basin

(Fig. 5.2)

Sl. No.	Gauge station	Name of the river or tributary	Hydraulic study unit	Year from which gauging is done	Method of gauging
1	2	3	4	5	6
1	Kushalnagar	Cauvery		1967	CM
2	Chunchanakatte	Cauvery	C_1	1916	CM
3	Krishnarajasagar	Cauvery		1934	RM
4	Bannur	Cauvery		1971	CM
5	Dhanagere	Cauvery		1922	WM
6	T. Narasipur	Cauvery	C_6	1966	CM
7	Sathyagala bridge site	Cauvery		1970	CM
8	Shivasamudram Anicut	Cauvery		1939	WM
15	Kambibane	Chicklihole		1966	WM
16	Hudgur	Harangi		1964	WM
17	Kudige bridge site	Harangi		1971	CM
18	Sakaleshpura	Hemavathi		1971	CM
19	Chikkabyadagere	Yagachi		1965	SA
20	Belur bridge	Yagachi		1968	CM
21	Madaghatta	Votehole	C_1	1968	CM
22	Chennanahalli	Votehole		1965	SA
23	Vidyapeeta	Tagachi		1971	CM
24	Gorur	Hemavathi		1966	SA
25	Srirama Devaru Anicut	Hemavathi		1950	WM
26	Akkihebbal	Hemavathi		1916	CM
27	Harihar	Lakshmanathirtha		1965	SA
28	Unduwadi	Lakshmanathirtha		1916	CM

Table 5.4 (...Contd.)

1	2	3	4	5	6
29	Srinivasa Agrahara	Lokapavani	C_6	1967	SA
33	Pura	Kabini		1956	CM
34	H.D. Kote	Taraka		1965	CM
35	Nugu dam site	Nugu		1961	RM
36	Hullahalli anicut	Kabini	C_2	1939	CM
37	Hullahalli bridge	Kabini		1970	CM
38	Nanjangud	Kabini		1966	SA
39	T. Narasipur	Kabini		1966	CM
41	Kollegal	Suvarnavathy	C_3	1965	CM
42	Marconahally	Shimsha		1940	RM
43	Muddanahalli	Shimsha		1967	SA
44	Kanva Reservoir	Kanva	C_4	1946	RM
45	T.K. Halli weir site	Shimsha		1942	VM
46	T.K. Halli bridge site	Shimsha		1970	CM
47	Chamarajasagar	Arkavathy		1939	RM
48	Manchanabele site	Arkavathy		1965	SA
49	Kanakapura bridge site	Arkavathy	C_5	1970	CM
50	Arobele	Arkavathy		1965	SA

Table 5.4 (...Contd.)

1	2	3	4	5	6
51	Chengawadi	Thattehalla		1961	CM
52	Rampur bridge site	Uduthorehalla	C_7	1970	CM
53	Manuganahalli	Doddihalla		1961	SA
54	Uggyam	Minnattuhalla		1966	SA

Observations given under column 6 indicate the method of gauging as:

CM Current meter
WM Weir calculation for flow
RM Reservoir operation
SA Slope area method

The locations of rain gauges and stream guage stations are shown in Fig. 5.2. The rain fall and run off records are available for most of the stations.

5.6.1 Ground water resources

The geological formulation is not favourable for ground water storage. However, some of the valley portions are filled with wash derived from the adjacent highlands. The area along the banks of some streams form a good aquifer for storage.

No systematic study has been done for the assessment of ground water potential in the basin. Raghava Rao et al., (1969) located some pockets of ground water areas. These are in the hydrologic study units, C_1, in Hemavathy sub-basin, C_4 and C_5, in Shimsha and Arkavathi basins, and in C_7, Uduthore-halla basins. The groud water potential of these regions is given in table 5.5.

Table 5.5

Ground Water potential

Area	Ground water potential in 100 Hect-m
C_1 - Hemavathy basin	90.00 units
C_4-C_5- Shimsha and Arkavathi basins	226.00 units
C_7 - Uduthore-halla	136.00 units

Generally open dug wells are used for exploitation of ground water. Several of these wells put together is considered as a unit. The locations of the units are shown in flow diagram (fig. 5.3).

5.7 Mathematical Model

Flow diagram (fig. 5.3) shows the main river with its tributaries, the location of various projects, irrigation districts, hydroelectric power stations and municipal and industrial demand locations. There are 100 nodes indicating junctions and diversions. The model is studied for two seasons, both Kharif and Rabi. The node numbers of figure 5.3 refer to those of Kharif season. The second season's (Rabi season) nodes are obtained by adding an arbitrary number say 150 to the nodes of the first season (Kharif). There are 487 arcs in the complete model (for both seasons). The flow diagram is summarized in table 5.6 to indicate the flows to and from the nodes. The number in a row with a positive (+ve) sign indicates the direction of flow to the node and the number with negative (-ve) sign indicates the direction of flow out of the node. For instance, at node 3 (column 1) the direction of flow is from the nodes 1 and 2 which have positive signs and outflow direction is to the node 7, which has negative sign. There is no power or irrigation diversions from this node 3.

There are two super nodes namely source node (299) and sink node (300). All inflows to the system and original reservoir levels

Fig. 5.3

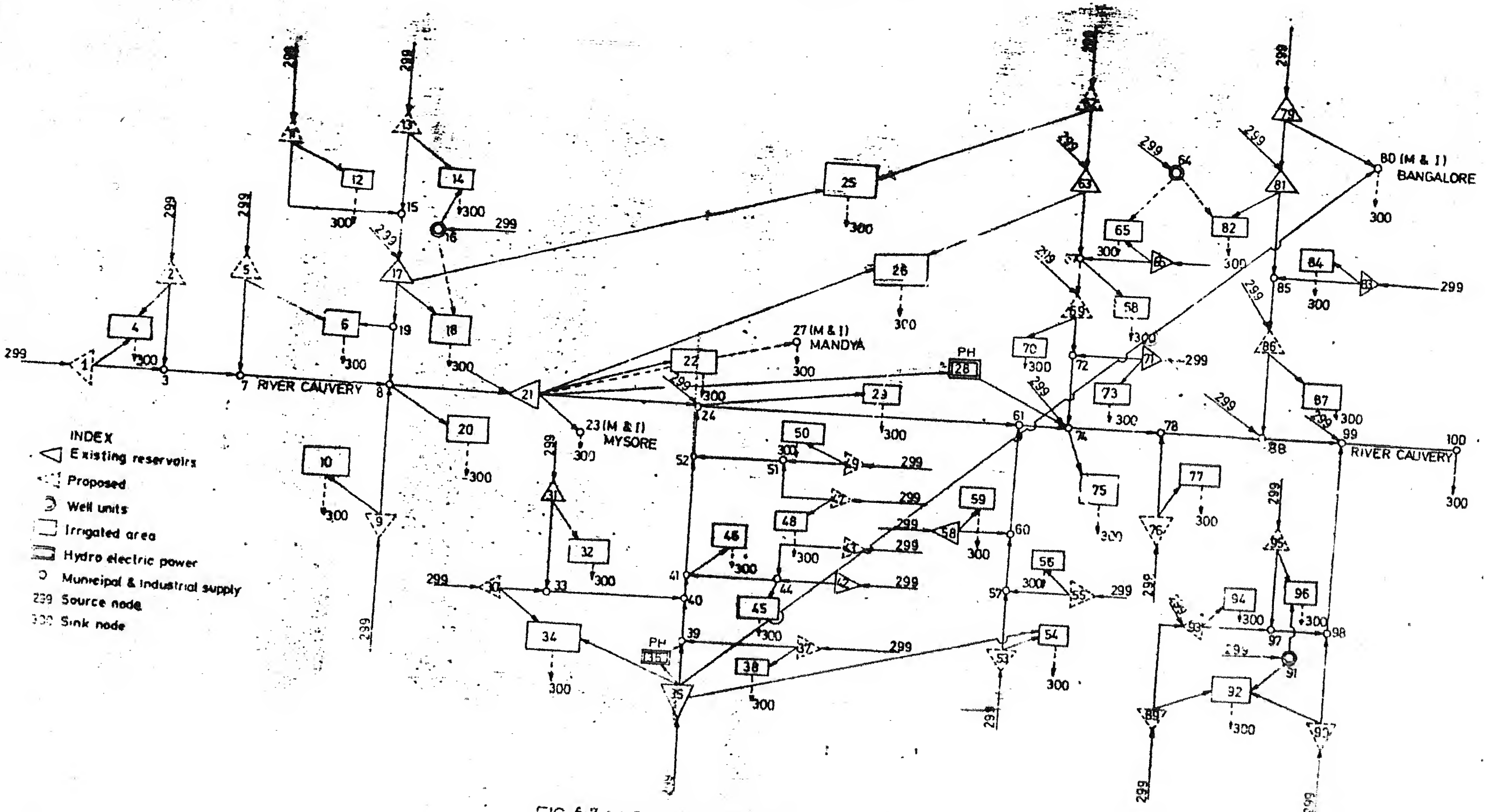


FIG.5.3 FLOW DIAGRAM OF CAUVERY BASIN MODEL

Table 5.6
Flow Diagram Details

Node	Channel flow					Irrigation				Power		M&I supply		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	+299	-3				-4								
2	+299	-3				-4								
3		+1	+2	-7										
4						+1	+2		-300					
5	+299	-7				-6								
6						+5	+19		-300					
7		+3	+5	-8										
8		+7	+9	+19	-21	-20								
9	+299	-8				-10								
10						+9			-300					
11	+299	-15				-12								
12						+11			-300					
13	+299	-15				-14								
14						+13	+16		-300					
15		+11	+13	-17										
16	+299					-14	-18							
17	+299	+15	-19			-18	-25							
18						+16	+17		-300					
19		+17	-8			-6								
20						+8			-300					

Table 5.6 (...Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
21	+299	+8	-24			-26	-22			-28		-23	-27	
22						+21			-300					
23												+21		-300
24	+299	+21	+52	-61		-29								
25						+17	+62		-300					
26						+21	+63		-300					
27												+21		-300
28										+21	-74			
29						+24			-300					
30	+299	-33				-34								
31	+299	-33				-32								
32						+31			-300					
33		+30	+31	-40										
34						+30	+35		-300					
35	+299					-34	-36	-54				-80		
36										+35	-39			
37	+299	-39				-38								
38						+37			-300					
39		+36	+37	+35	-40									
40		+33	+39	-41										
41		+40	+44	-52		-46								
42	+299	-44												
43	+299	-44												

Table 5.6 (...Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
44		+42	+43	-41		-45								
45						+44			-300					
46						+41			-300					
47	+299	-51				-48								
48						+47			-300					
49	+299	-51				-50								
50						+49			-300					
51		+47	+49	-52										
52		+41	+51	-24										
53	+299	-57				-54								
54						+53	+35		-300					
55	+299	-57				-56								
56						+55			-300					
57		+53	+55	-60										
58	+299	-60				-59								
59						+58			-300					
60		+57	+58	-61										
61		+24	+60	-74										
62	+299	-63				-25								
63	+299	-67				-26								
64	+299					-65	-82							
65						+64	+66		-300					

Table 5.6 (...Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
66	+299	-67				-65								
67		+63	+66	-69		-68								
68						+67			-300					
69	+299	+67	-72			-70								
70						+69			-300					
71	+299	-72				-73								
72		+69	+71	-74										
73						+71			-300					
74	+299	+61	+28	+72		-75								
75						+74			-300					
76	+299	-78				-77								
77						+76			-300					
78		+74	+76	-88										
79	+299	-81										-80		
80												+79	+35	-300
81	+299	+79	-85			-82								
82						+64	+81		-300					
83	+299	-85				-84								
84						+83			-300					
85		+81	+83	-86										
86	+299	+85	-88			-87								
87						+86			-300					
88	+299	+78	+86	-99										

Table 5.6 (...Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
89	+299	-93				-92								
90	+299	-98				-92								
91	+299					-92	-96							
92						+89	+90	+91	-300					
93	+299	+89	-97			-94								
94						+93			-300					
95	+299	-97				-96								
96						+95	+91		-300					
97		+93	+95	-98										
98		+90	+97	-99										
99	+299	+88	+98	-100										
100		+99			-300									

Note: 299 source node

300 sink node

Plus sign indicates flow coming into the node

Minus sign indicates flow leaving the node.

originate from the source node. All exit flows and final reservoir levels are removed to the sink node. An artificial arc is introduced connecting sink node to source node to complete the circulation network. Figure 5.3 gives the details of flow inputs and outputs of the system.

5.8 Economic Characteristics of the System

Costs and benefits of the system are required to formulate the mathematical programming model. The capital cost, and the operations, maintenance and replacement costs are obtained from the project reports. The costs of well projects are estimated after getting relevant data from individual well owners and officials of Central Ground Water Board.

The benefits from irrigation are estimated using land revenue values since water rates are collected in the form of land revenues. The returns from power and municipal and industrial water supplies are estimated using the data provided by Karnataka Electricity Board and Bangalore Water Supply & Sewarage Boards (Appendix A). Nayak and Arora (1971) reported that it is enough to know the relative economic values rather than actual values of the projects for scheduling and sequencing problems.

The major uses of water in Cauvery river basin are irrigation, hydroelectric power and municipal and industrial water supplies. Other uses like recreation and ecology are implicitly taken into consideration by providing minimum pool level in some

reservoirs. Irrigation is a major sector which requires large percentage of water available in the basin (nearly 70% or more).

5.9 Existing Facilities

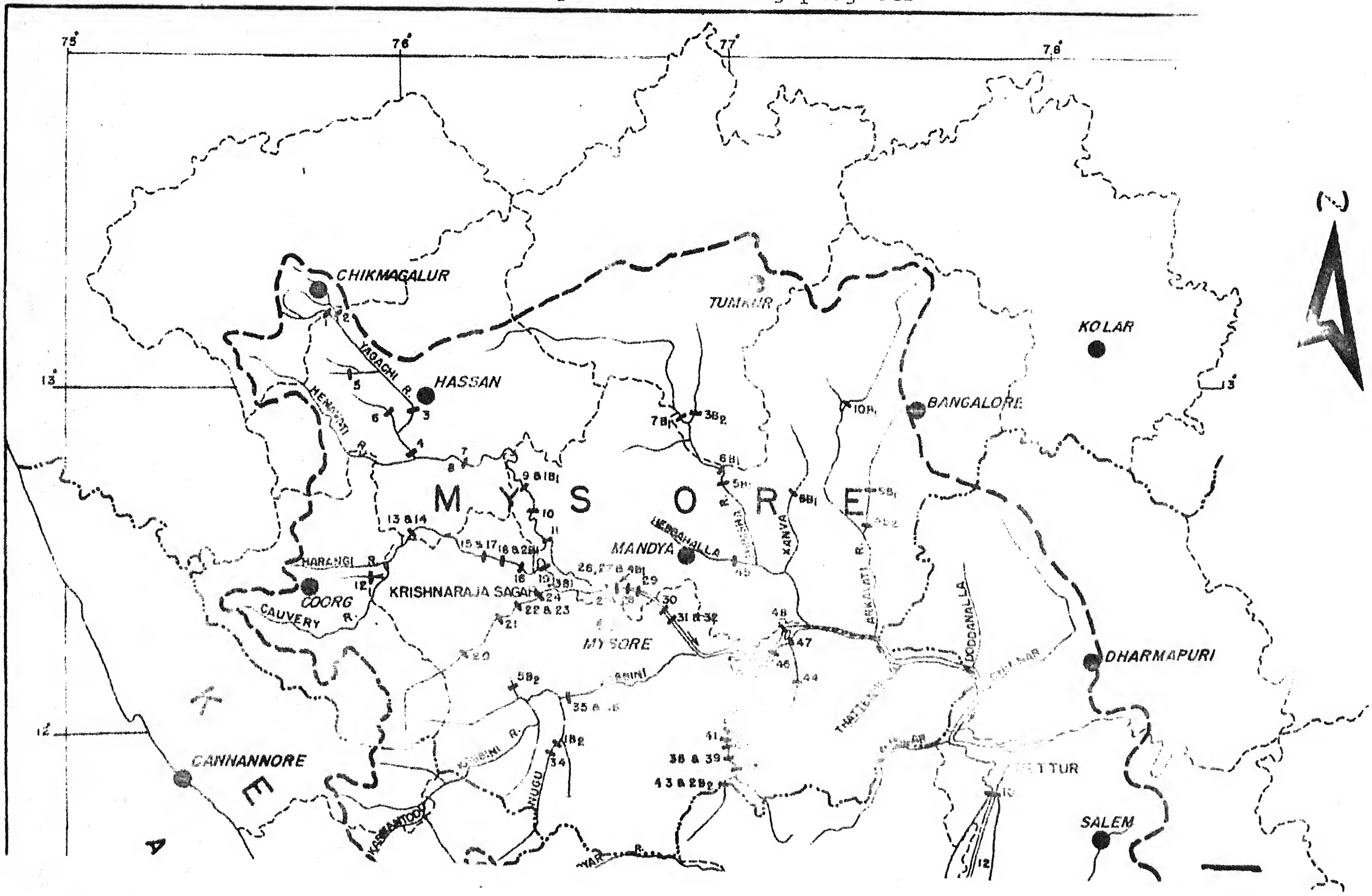
There are 12 existing reservoirs which supply water for irrigation, municipal and industrial supplies and for power generation. Table 5.7 gives the details of these projects (figs. 5.3 and 5.4).

Table 5.7

Existing projects

Sl.No.	Node No.	Project	Capacity (100 Hect-m)	Purpose
1	17	Hemavathy	960.00	Irrigation
2	21	Krishnarajasagar	1140.00	Irrigation, power & recreation
3	31	Hebballa	11.00	Irrigation
4	35	Kabini	541.00	Irrigation & power
5	42	Nugu	122.00	Irrigation
6	58	Chikkahole	10.00	Irrigation
7	63	Marconahalli	64.00	Irrigation
8	66	Mangala	7.00	Irrigation
9	71	Kanva	18.00	Irrigation
10	79	Chamarajasagar	82.00	M&I supply
11	81	Manchanabele	39.00	Irrigation
12	83	Byramangala	17.00	Irrigation

Fig. 5.4 Existing projects



Details of Fig. 5.4

Existing Projects

	Project	Main River
1	Kittur anicut	Hemavathy
2	Kudlur anicut	
3	Haluvagilu anicut	
4	Chandravalli anicut	
5	Kodihalli anicut	
6	Shankartheertha anicut	
7&8	Sreeramadevaru anicut	
9&1B$_1$	Mandagere anicut	
10	Hemagiri anicut	
11	Kallahalli anicut	
12	Chiklihole anicut	Chiklihole
13&2B$_1$	Ramanathapura anicut	Cauvery u/s of Krishnarajasagara
14	Kattepur anicut	
15&17	Chamaraja anicut	
16	Mirle anicut	
18	Ramasamudram anicut	
19	Tippur anicut	
20	Hanagode series anicut	Suvarnavathy
21	Katte malalawadi anicut	
22&23	Siriyur canal anicut	
24	Marachalli Awandur	

Details of Fig. 5. (...Contd.)

25	Devaraja anicut	
26,27 & 4B$_1$	Viriginadi anicut	
28	Yadathittu anicut	Cauvery d/s of Krishnarajasagar
29	Bangaradoddi anicut	
30	Mahadevapura anicut	
31	Ramaswamy anicut	
32	Rajaparameswari anicut	
33	Madhavamantri anicut	
34	Lakshmanapura anicut	Kabini
35&36	Hullahalli anicut	
37	Honglawadi anicut	
38&39	Saragur anicut	
40	Alur anicut	Suvarnavathi
41	Muralahalli anicut	
42	Hosahalli anicut	
43	Bandikere anicut	
44	Gundal anicut	Gundal
45	Maddur anicut	Shimsha
46	Dhangare anicut	
47	Seven anicuts	
48	Sivasamudra anicut	
3B$_1$	Krishnarajasagar	Cauvery
5B$_1$	Thaggehalli anicut	

Details of Fig. 5.4 (...Contd.)

$6B_1$	Chandanahalli anicut	
$7B_1$	Marconahalli	Shimsha
$8B_1$	Kanva	
$9B_1$	Byramangala	Arkavathi
$10B_1$	Chamarajasagar	
$1B_2$	Nugu	Kabini
$2B_2$	Chikkahole	Suvarnavathi
$3B_2$	Mangala	Shimsha
$4B_2$	Suvarnamukhi anicut	Arkavathi
$5B_2$	Hebbahalla	Kabini
$2C_1$	Hemavathy	Hemavathy
$5C_1$	Kabini	Kabini
$9C_1$	Manchanabele	Arkavathi

The first dam constructed was Krishnarajasagar in the year 1931. In the last two decades, 11 more projects are constructed. Obviously no interdependencies were considered in planning and designing these projects. Besides, there are a number of minor irrigation schemes consisting of diversion works and tanks in the basin. The details of these schemes are given in fig. 5.4.

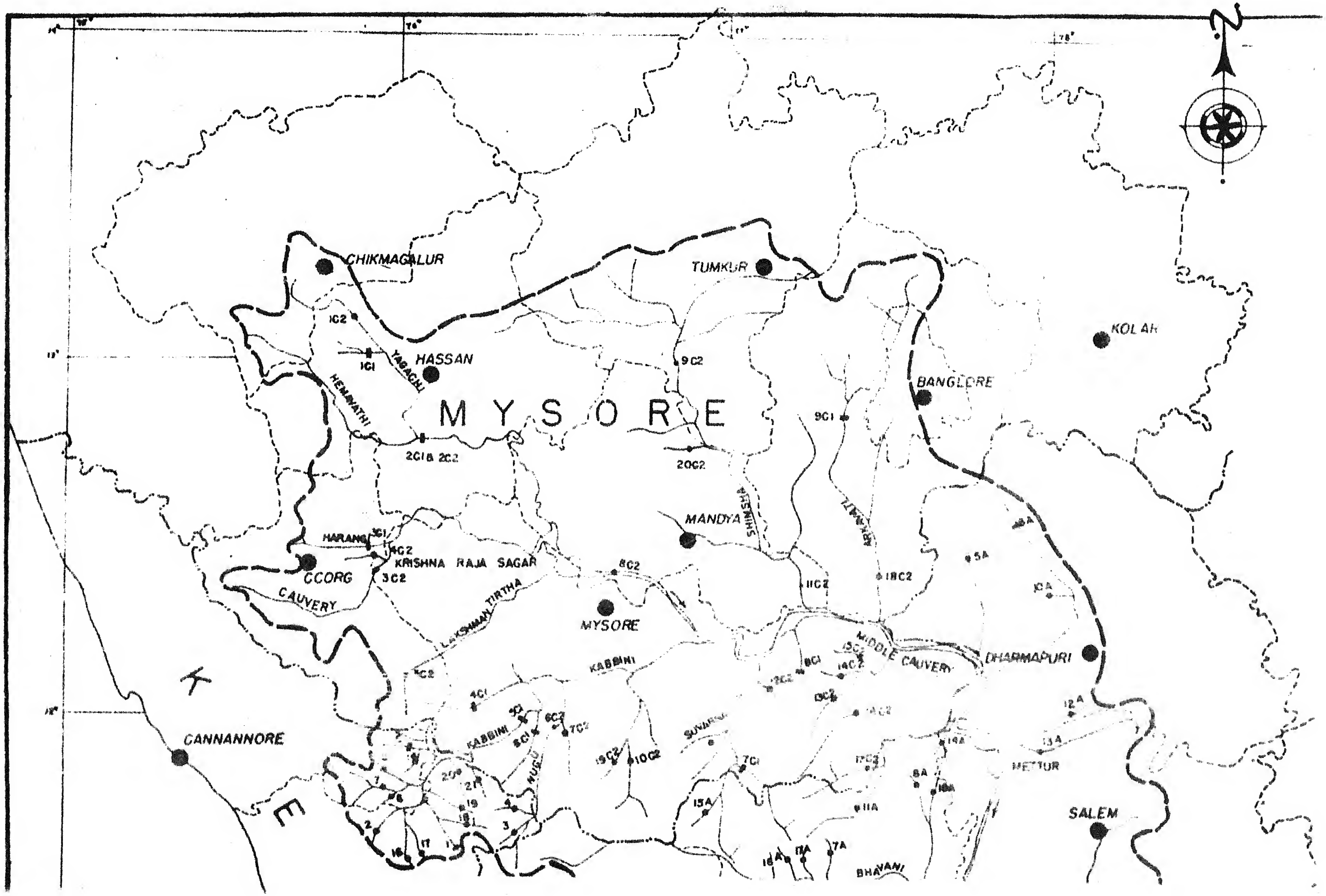
5.10 Potential Projects

On the basis of India Meterological Department (IMD) identification of drought areas, Karnataka has nearly 21,500 sq.km of such areas in the Cauvery basin itself (Irrigation Commission, 1972). Thus, major portion of the basin area is drought affected. Therefore, it is necessary to augment the irrigation supplies by constructing projects to impound water and exploit the available ground water potential.

There are twenty one potential sites where dams can be constructed and also there are 3 locations for well fields.

In the present analysis, it is assumed that at each site three different scales of projects can be constructed and each scale of development is treated as a separate project. Table 5.9 summarizes the details of all potential surface water projects and table 5.9 gives the details of ground water projects (fig. 5...

Fig. 5.5 Potential projects



Details of Fig. 5.5

New Projects

$1C_1$	Vetehole reservoir
$3C_1$	Harangi reservoir
$4C_1$	Taraka reservoir
$6C_1$	Sagare doddakere reservoir
$7C_1$	Suvarnavathi reservoir
$8C_1$	Gundal reservoir
$1C_2$	Yagachi reservoir
$3C_2$	Hosapatna reservoir
$4C_2$	Chiklihole reservoir
$5C_2$	Lakshmanatheertha reservoir
$7C_2$	Mudregundihalla reservoir
$9C_2$	Upper Shimsha reservoir
$10C_2$	Nalluru amanikere reservoir
$11C_2$	Iggalur reservoir
$12C_2$	Hebbadahalla reservoir
$13C_2$	Belthur reservoir
$14C_2$	Changawadi reservoir
$15C_2$	Doddihalla reservoir
$16C_2$	Uduthorehalla reservoir
$18C_2$	Arkavathi reservoir
$19C_2$	Devalapura reservoir

Table 5.8

Potential surface reservoir projects

Sl.No.	Node No.	Project	Maximum capacity (100 Hect-m)	Remarks
1	1	Hosapatna	145.00	
2	2	Chiklihole	6.00	
3	5	Harangi	183.00	
4	9	Lakshmanatheertha	19.00	
5	11	Votehole	28.00	
6	13	Yagachi	27.00	
7	30	Taraka	74.00	
8	37	Sagaredoddakere	6.00	
9	43	Kudregundihalla	8.00	
10	47	Devalapura	7.00	All are irrigation projects
11	49	Nalluruamanikere	29.00	
12	53	Suvarnavathi	31.00	
13	55	Hebbadahalla	4.00	
14	62	Upper Shimsha	57.00	
15	69	Iggalur	6.00	
16	76	Gundal	30.00	
17	86	Arkavathi	42.00	
18	89	Belthur	5.00	
19	90	Uduthorehalla	22.00	
20	93	Changawadi	8.00	
21	95	Doddihalla	4.00	

Table 5.9

Ground water potential

Sl. No.	Node No.	Location (Hydrological unit)	Max. capacity (100 Hect-m)
1	16	C_1	90.00
2	64	C_4 and C_5	226.00
3	91	C_7	136.00

5.11 Deterministic Model

The inflows to the system are assumed to be known with certainty. Only mean annual flows are taken in the analysis, since extreme event design for one purpose may not be suited for other purposes. Input to the system at different points are taken from historical records.

As mentioned earlier at every site different scales of developments are taken as separate projects. There are sixty projects in total, i.e. 12 existing projects and forty-eight new projects.

With economic and physical characteristic of the system outlined, the objective function to be maximized is:

Maximize the present value of net benefits, Z

where

$$Z = \sum_{t_s=1}^{30} \lambda_{t_s} \sum_{k=1}^{12} A_{kt_s} + \sum_{t_s=1}^{30} \lambda_{t_s} \sum_{k=13}^{60} g_{kt_s} A_{kt_s}$$

$$- \sum_{t_s=1}^{30} \lambda_{t_s} \sum_{k=13}^{60} g_{kt_s} C_{kt_s} - \sum_{t_s=1}^{30} \lambda_{t_s} \sum_{k=1}^{12} O_{kt_s}$$

$$- \sum_{t_s=1}^{30} \lambda_{t_s} \sum_{k=13}^{60} g_{kt_s} O_{kt_s} \qquad (5.11.1)$$

where A_{kt_s} is a function of irrigation water supply, power supply and municipal and industrial water supplies, i.e., $A_{kt_s} = \sum_t (45 I_{kt} + 96\ P_{kt} + 1000\ M_{kt})$ $t = 1,2$

1 = Kharif

2 = Rabi

Budgetary constraints

$$\sum_{k=13}^{60} g_{kt_s} C_{kt_s} \leq 10{,}000{,}000 \text{ for all } t_s$$

Institutional constraints

$$\sum_{k=13}^{60} g_{kt_s} \leq 1 \text{ for all } t_s$$

In any year only one project is introduced.

$$\sum_{t_s=1}^{30} \sum_{k\varepsilon k'} g_{kt_s} \leq 1$$

where k' = number of different scales of project that can be constructed at any site. For example, at node 1, one of the projects, 13 & 14 may be constructed (if at all to be constructed).

$$\sum_{t_s=1}^{30} g_{kt_s} \leq 1$$

A project can be constructed only once.

Contingent projects

The project at node point 13 is contingent with the project at node point 12.

The constraint is written as

$$g_{23/24}t_s \leq g_{21/22}t_s$$

Demand constraints

The demand for water comprises of irrigation demand, power demand and municipal and industrial water supply demand. Most of the projects in the basin are irrigation projects. The projects at node points (fig. 5.3) at 21 and 35 are multipurpose projects supplying water for irrigation, power and municipal and industrial supply. The project at node point 79 is only municipal and industrial water supply project. Hence demand constraints can be written as

$X_{kt} \geq I_{kt}$ for $t = 1,2$
and k for all projects except projects at 21, 35 and 79

$X_{kt} \geq I_{kt} + P_{kt} + W_{kt}$ for $t = 1,2$
and for k = projects at 21, 35.

$X_{kt} \geq W_{kt}$ for $t = 1,2$
and $k = 79$.

It can be seen from the fig. 5.3 that some of the agricultural districts are supplied with water from more than one project. These irrigations are jointly constrained.

$$\sum_{k \epsilon k_s} X_{kt} \leq AL_t$$

K_s = set of projects supplying water to some irrigation district

AL_t = maximum irrigable land with supply from k_s projects expressed in the unit of water.

i.e. irrigation districts 6, 14, 18, 25, 26, 34, 45, 54, 65, 82, 92 and 96 are supplied with water from more than one project.

Maximum storage constraint

$$S_{kt} \leq V_{kt} \quad \text{for all } k \text{ and } t$$

Minimum storage constraint

$$S_{kt} \geq S_{kt}^{min} \quad \text{for } k = 21,\ 35 \text{ and } 79$$

$$t = t_1 \text{ and } t_2$$

Continuity equation

$$S_{kt} = S_{kt-1} + R_{kt} - X_{kt} \quad \text{for all } k$$

$$\text{and } t = t_1 \ \& \ t_2$$

Canal constraints

$$X_{tm} \leq H_m \quad \text{for all arcs}$$

$$X_{tm} \geq L_m \quad \text{for all arcs}$$

The values of H_m and L_m are given in table (B-2)

Continuity equation at each node.

At each of the nodes total inflow into the node and total outflow from the node must be equal

$$\sum_j x_{ij} - \sum_j x_{ji} = 0 \quad \text{for } i = 1,2,\ldots 300.$$

and

$$g_{kt_s} = 0 \text{ or } 1 \quad \text{for all } k \text{ and } t_s.$$

5.12 Stochastic Model

As mentioned in Chapter 3 only natural inflows to the system are taken as random variables. The probability density coefficients for all stream are obtained using Kim's (1968) method. This method is used to describe the flow level probability. The method consists of deriving from annual stream flow data discrete points. From the historical data mean and standard deviations are calculated. The minimum annual flow is taken as first discrete point. The sixth discrete point is the maximum annual stream flow. The remaining points are obtained by adding to the preceding point, the quotient of the difference of maximum and minimum annual flows divided by five.

Then the probability density coefficient for each interval is obtained by the following expression

$$\text{Probability density coefficient} = F\left(\frac{R_{i+1} - \bar{R}}{s_R}\right) - F\left(\frac{R_i - \bar{R}}{s_R}\right)$$

$$\text{for } i = 1, 2, 3 \ldots, 6$$

R_i = discrete point

$\bar{R}$ = annual mean stream flow

s_R = standard deviation

and F = normal cumulative distribution function.

From these probability densities, cumulative distribution function is obtained.

The cumulative distribution graph is obtained for all streams. Since this involves a large amount of data, only a few representative cumulative distributions are given (fig. 5.6).

In the analysis 75 percent probability is used for the constraints involving stochastic variables.

The details of chance constrained formulation with linear decision rule is given in Chapter 3. In the present chapter the application of this formulation is briefly presented.

As mentioned before, reservoirs at node points 1, 2, 5, 9, 13, 30, 35, 37, 42, 43, 47, 49, 53, 55, 58, 62, 66, 71, 76, 79, 89, 90 and 95 are independent reservoirs since inflows to these reservoirs are the only natural flows. Let these reservoirs be denoted by a sub-set G

i.e., G = (1, 2, 5, 9, 13, 30, 35, 37, 42, 43, 47, 49, 53, 55, 58, 62, 66, 71, 76, 79, 83, 89, 90, 95).

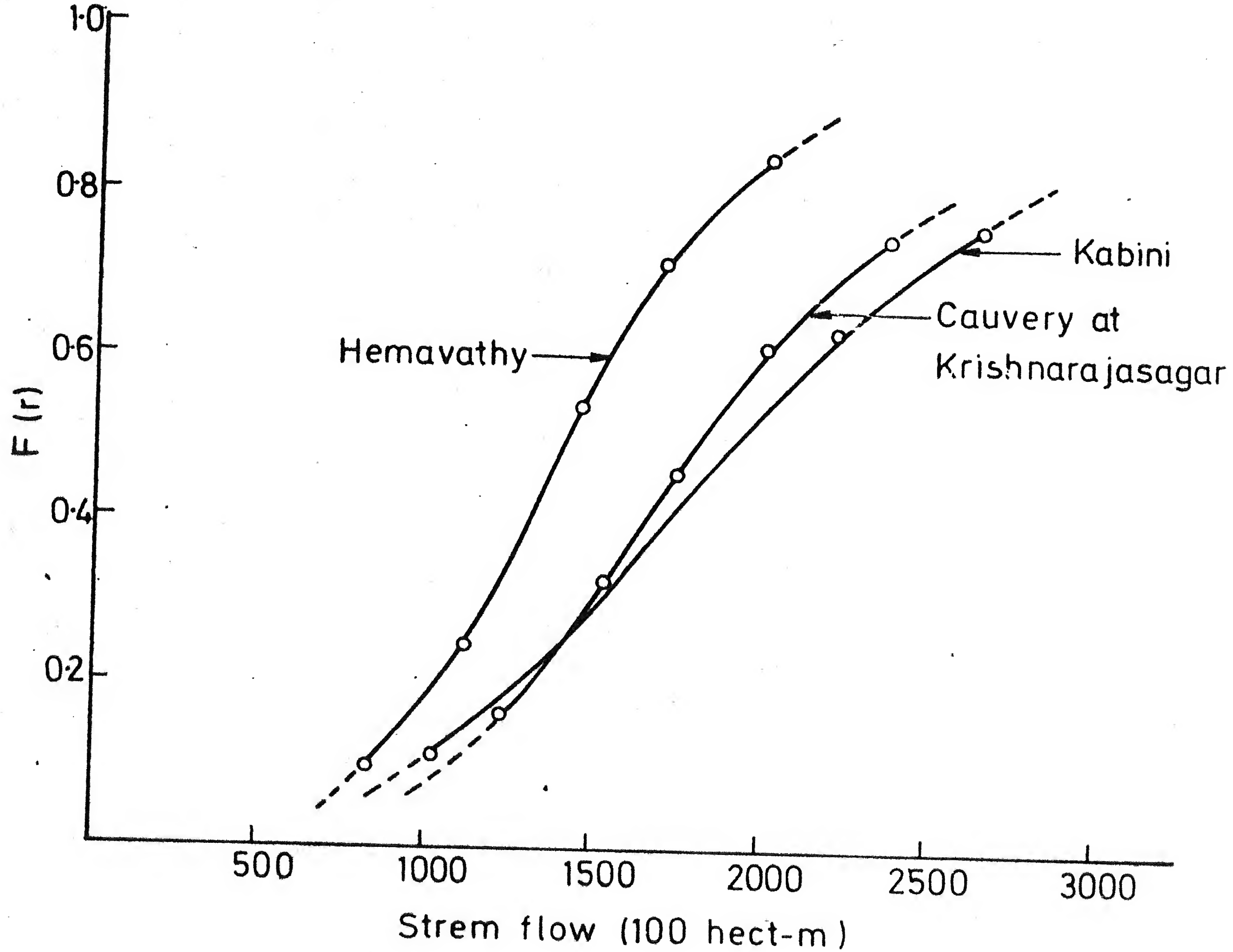


FIG.5.6 CUMULATIVE DISTRIBUTION CURVE

The inflows to the reservoirs at nodes 17, 21, 63, 69, 81, 86 and 93 consist of natural flows plus certain portion of releases from the respective upstream reservoirs. These reservoirs are called dependent reservoirs and denoted by a sub-set H,

i.e., H = (17, 21, 63, 69, 81, 86, 93).

Hence the complete set of reservoirs is the union of G and H sub-sets.

The linear decision rule for the independent reservoir sub-set G will become (Refer equations 3.3.6 and 3.3.8),

$$S_{Gt} = R_{Gt} + b_{Gt} \quad \text{for } G\ (1,2,5\ldots,95)$$

$$\text{and } t = t_1 \ \&\ t_2$$

$$X_{Gt} = R_{Gt-1} + b_{Gt-1} - b_{Gt}$$

Similarly for dependent reservoir sub-set H the linear decision rule (Refer equations 3.3.12 and 3.3.18).

$$S_{Ht} = R_{Ht} + b_{Ht}$$

and $$X_{Ht} = R_{Ht} + b_{Ht-1} - b_{Ht} + \sum_{G \in k_{up}} \{\psi_{Gt}(R_{Gt-1} + b_{Gt-1} - b_{Gt})\}$$

for all H (17, 21, ... 93)

$t = t_1 \ \&\ t_2$

where k_{up} = respective u/s reservoirs.

Equations (3.3.13 & 3.3.16) are used to convert stochastic constraints to equivalent deterministic constraints.

The minimum release constraint takes the form for independent reservoir set G

$$1 - F_R \; (D_{Gt} - b_{Gt-1} + b_{Gt}) \geq 0.75$$

$$F_R \; (D_{Gt} - b_{Gt-1} + b_{Gt}) \leq (1 - 0.75)$$

$$D_{Gt} - b_{Gt-1} + b_{Gt} \leq F^{-1} \quad (0.25)$$

for dependent reservoirs sub-set H

$$D_{Ht} + b_{Ht} + b_{Ht-1} + \sum_{k \varepsilon k_{up}} (\psi_{kt} \; b_{kt} - \psi_{kt-1} \; b_{kt-1}) \qquad F^{-1}(0.25)$$

Similarly minimum storage constraints for independent reservoir sub-set G will be

$$S_{Gt}^{min} \; - \; b_{Gt} \leq F_R^{-1} \; (0.25)$$

for dependent reservoir sub-set H

$$S_{Ht}^{min} - b_{Ht} \leq F_R^{-1} \; (0.25)$$

The normal distribution is taken for all reservoir inflows.

5.13 Model with Evaporation Losses

Since the basin lies in semi-arid region the evaporation losses from water surfaces are quite considerable. As mentioned in Chapter 3 the evaporation losses are given by an expression $E_{kt} = \delta_{kt} \; (S_{kt} + S_{kt-1})$. These losses are estimated using meteorological data, since available data is too meagre. The area-capacity curves are obtained using elevation-area and

elevation-storage curves which are available in project reports of different dams (fig. 5.7a,5.7b). The evaporation parameter δ_{kt} for Kharif and Rabi seasons is obtained by fitting a straight line to the losses at different storage levels. The values of δ_{kt} are given in table 5.10.

Table 5.10

Values of evaporation parameter δ_{kt}

Sl. No.	Node No. (Fig. 5.5)	Reservoir	Values of δ_{kt}	
			Kharif season	Rabi season
1	2	3	4	5
1				
1	1	Hosapatna	0.030	0.100
2	2	Chiklihole	0.030	0.100
3	5	Harangi	0.035	0.120
4	9	Lakshmanatheertha	0.035	0.120
5	11	Vetehole	0.035	0.120
6	13	Yagachi	0.040	0.125
7	17	Hemavathy	0.040	0.130
8	21	Krishnarajasagar	0.045	0.130
9	30	Taraka	0.040	0.120
10	31	Hebballa	0.040	0.110
11	35	Kabini	0.040	0.100
12	37	Sagaredoddakere	0.040	0.120
13	42	Nugu	0.045	0.120
14	43	Kudregundihalla	0.045	0.125

Table 5.10 (...Contd.)

1	2	3	4	5
15	47	Devalapura	0.045	0.125
16	49	Nalluruamanikere	0.046	0.125
17	53	Suvarnavathi	0.047	0.125
18	55	Hebbadahalla	0.047	0.120
19	58	Chikkahole	0.047	0.120
20	62	Upper Shimsha	0.050	0.130
21	63	Marconahalli	0.050	0.130
22	66	Mangala	0.050	0.130
23	69	Iggalur	0.050	0.125
24	71	Kanva	0.051	0.130
26	79	Chamarajasagar	0.052	0.130
27	81	Manchanabele	0.052	0.130
28	83	Byramangala	0.051	0.130
29	86	Arkavathi	0.052	0.130
30	89	Belthur	0.055	0.140
31	90	Uduthorehalla	0.055	0.150
32	93	Changawadi	0.060	0.150
33	95	Doddihalla	0.060	0.150

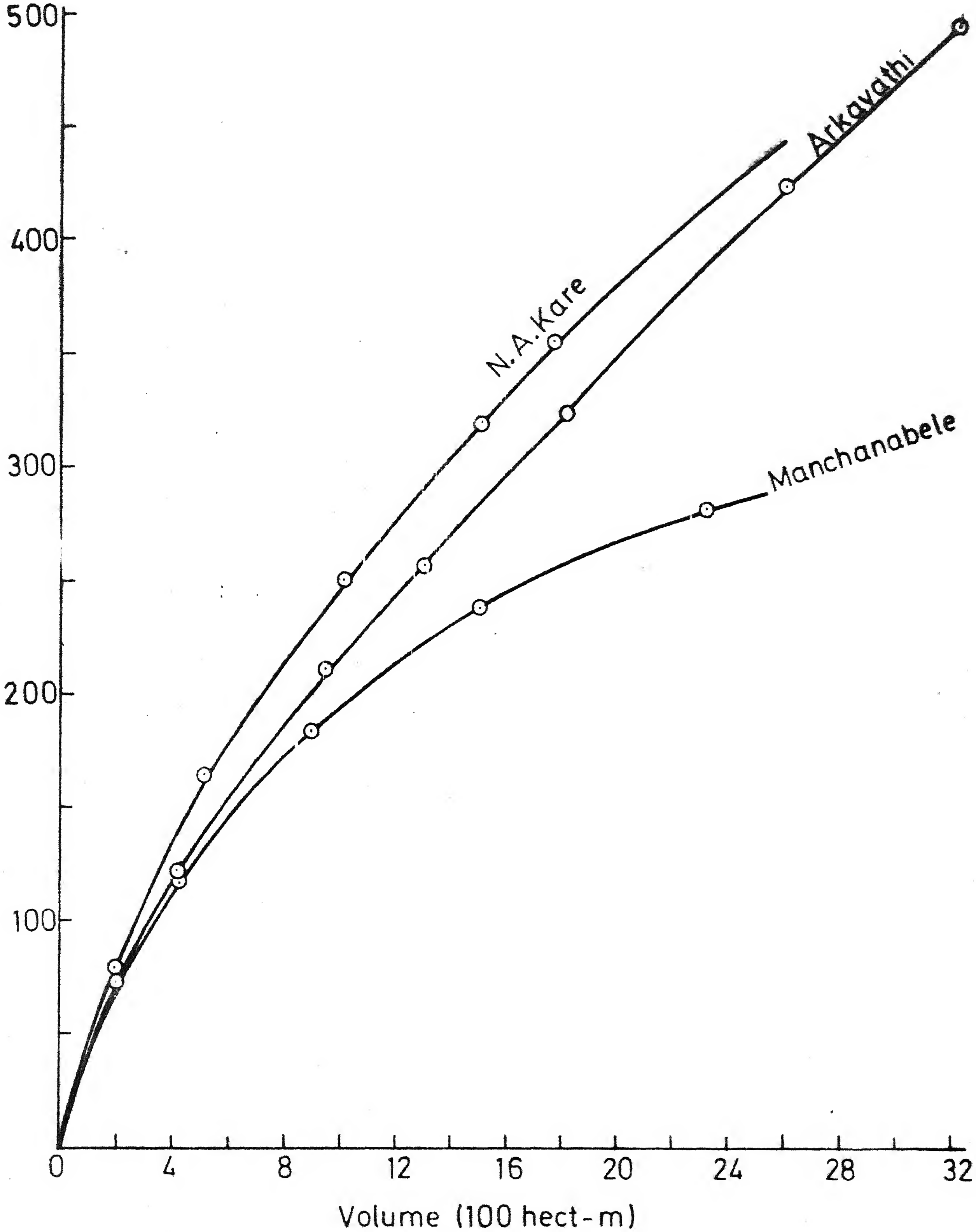


FIG. 5.7(a) AREA VOLUME CURVES

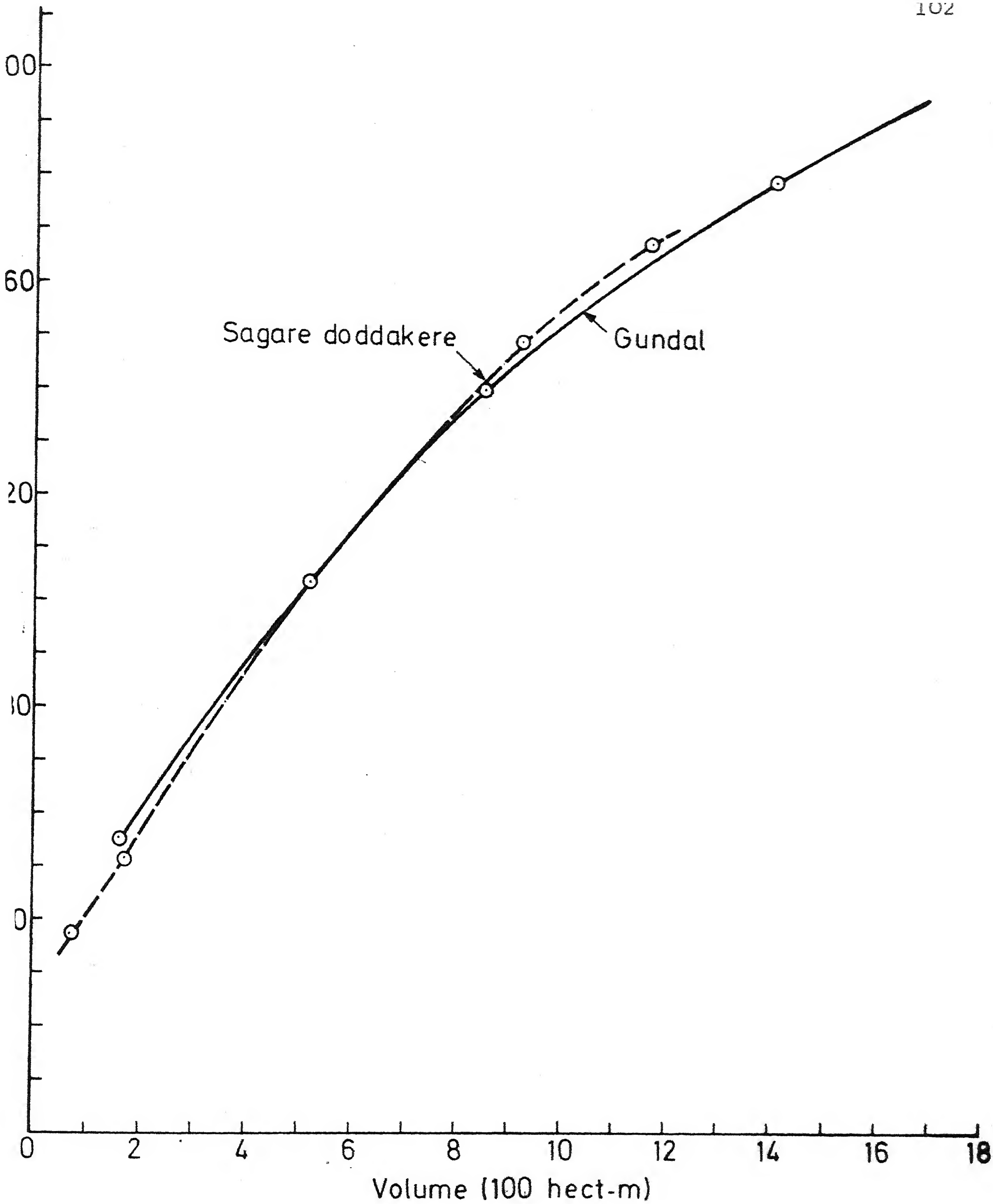


FIG.5.7(b) AREA VOLUME CURVES

In the stochastic model with evaporation losses the objective function and the constraints except the minimum release and the minimum storage constraints remain same as those of previous model. Hence complete model is not repeated. However, the minimum release constraint and minimum storage constraint are modified using the values of ξ_{kt}.

From section 3.5 the linear decision rule for independent reservoir sub-set G, (G = 1, 2, 5, ...) will be

$$X_{Gt} = \frac{\eta_{Gt}}{\theta_{Gt-1}} \{R_{Gt-1} + b_{Gt-1}\} - b_{Gt}$$

and $S_{Gt} = (R_{Gt} + b_{Gt})/\theta_{Gt}$

Then the minimum release constraint will be

$$P\{X_{Gt} \geq D_{Gt}\} \geq .75$$

$$P\left\{\frac{\eta_{Gt}}{\theta_{Gt-1}} (R_{Gt-1} + b_{Gt-1}) - b_{Gt} \geq D_{Gt}\right\} \geq 0.75$$

$$(b_{Gt} + D_{Gt}) \frac{\theta_{Gt-1}}{\eta_{Gt}} - b_{Gt-1} \leq F^{-1}(0.25)$$

The minimum storage constraint will be

$$P(S_{Gt} \geq S_{Gt}^{min}) \geq 0.75 \qquad \text{for } t = 1,2$$

$$G = (1,2,5...)$$

$$P\left\{\frac{R_{Gt} + b_{Gt}}{\theta_{Gt}} \geq S_{Gt}^{min}\right\} \geq 0.75$$

$$F(S_{Gt}^{min}\,\theta_{Gt} - b_{Gt}) \leq 0.25$$

$$S_{Gt}^{min}\,\theta_{Gt} - b_{Gt} \leq F^{-1}(0.25)$$

For dependent reservoir sub-set H (H = 17,21,...) the linear decision rule will be

$$X_{Ht} = \frac{\eta_{Ht}}{\theta_{Ht-1}} \left\{ R_{Ht-1} + b_{Ht-1} \right\} + \sum_{G \epsilon k_{up}} \psi_{Gt} X_{Gt} - b_{Ht}$$

and

$$S_{Ht} = \frac{R_{Ht} + b_{Ht}}{\theta_{Ht}}$$

With these values for X_{Ht} and S_{Ht}, the minimum release and minimum storage constraints takes the form of

$$\left\{ (b_{Ht} + D_{Ht}) - \sum_{G \epsilon k_{up}} \psi_{Gt} X_{Gt} \right\} \frac{\theta_{Ht-1}}{\eta_{Ht}} - b_{Ht-1} \leq F^{-1} \ (0.25)$$

and

$S_{Ht}^{min} \theta_{Ht} - b_{Ht} \leq F^{-1}$ (0.25) respectively.

5.14 Data Details

The above models are solved using the methodology explained in Chapter 4. Table 5.11 shows the location, physical and economic data of projects. Any of the different scales of development may be built at each location. It can also be seen that projects 13 or 14 may be constructed at site number 1 and 15 and 16 at site number 2, etc.

5.15 Network Details

As mentioned earlier, a year is divided into two periods Kharif and Rabi. Appendix B gives the details of all arcs,

Table 5.11

Physical and economic data of projects

Sl. No.	Node No.	Max. capacity (100 Hect-m)	Investment (Rs. 10^6)	Maximum annual return (Rs. 10^5)
1	2	3	4	5
Existing projects				
1	17	960.00		
2	21	1140.00		
3	31	11.00		
4	35	541.00		
5	42	122.00		
6	58	10.00		
7	63	64.00		
8	66	7.00		
9	71	18.00		
10	79	82.00		
11	81	39.00		
12	83	17.00		
New projects				
13	1	145.00	227.00	14.50
14	1	110.00	200.00	11.00
15	2	6.00	15.40	0.60
16	2	3.00	10.00	0.30
17	5	183.00	110.00	18.30
18	5	140.00	82.00	14.00
19	9	19.00	15.50	1.90
20	9	12.00	9.00	1.20
21	11	28.00	19.90	2.30
22	11	20.00	13.50	2.00
23	13	27.00	71.20	2.70
24	13	20.00	55.00	2.00

Table 5.11 (...Contd.)

1	2	3	4	5	
25	16	35.00	35.60	6.00	
26	16	30.00	31.50	4.00	
27	30	74.00	39.50	7.40	
28	30	60.00	37.00	6.00	
29	37	6.00	9.00	0.60	
30	37	3.00	8.00	0.30	
31	43	8.00	14.00	0.80	
32	43	4.00	10.00	0.40	
33	47	7.00	16.00	0.70	
34	47	4.00	12.00	0.40	
35	49	29.00	19.00	2.90	
36	49	15.00	12.00	1.50	
37	53	31.00	24.80	3.10	
38	53	25.00	16.20	2.50	
39	55	4.00	9.80	0.40	
40	55	2.00	7.00	0.20	
41	62	57.00	62.00	5.70	
42	62	40.00	52.00	4.00	
43	64	20.00	31.00	6.00	[illegible].20
44	64	15.00	18.00	4.00	
45	69	2.00	18.00	0.20	
46	69	1.00	13.20	0.10	
47	76	30.00	29.60	3.00	
48	76	20.00	22.25	2.00	
49	86	42.00	37.65	4.20	
50	86	30.00	20.25	3.00	
51	89	5.00	14.20	0.50	
52	89	3.00	11.00	0.30	
53	90	22.00	46.80	2.20	

Table 5.11 (...Contd.)

1	2	3	4	5
54	90	15.00	38.35	1.50
55	91	20.00	25.00	3.50
56	91	15.00	15.00	2.00
57	93	8.00	8.60	0.80
58	93	5.00	6.20	0.50
59	95	4.00	7.70	0.40
60	95	2.00	6.25	0.20

upper bound, lower bound, value of return from one unit (1 Hect-m) of water through each arc of the system and initial flows.

The inflow to the system (natural stream flows arcs 1 through 40 for Kharif season and arcs 225 through 264 for rabi season) and original reservoir levels (arcs 41 through 76) originate from source node 299. The flows in arcs, i.e. arcs 1 through 40 arcs 225 through 264 and arcs 41 through 76 are assured by setting the upper and lower bounds of these arcs at the same value. All exit flows from the system (arc 403 through 485) and all final reservoir volumes (arcs 377 through 412 are removed to the sink node 300. The artificial arc 487 connects the sink node to source node 299 to complete the circulation of network.

Stream flow records are available for all the streams. The length of the records are not the same for all the streams. Since it is a voluminous data, listing all the data is not feasible. Only annual mean flow values and 25 per cent probability values are given in table 5.12.

5.16 Demands for Water

The analysis is considered under the basic demand pattern of irrigation, power and municipal and industrial supplies. The demands for power and municipal and industrial (Table 5.12)

Table 5.12

Stream flow data

(100 Hect-m)

Sl. No.	Stream	Kharif 25 per-centile	Kharif 50 per-centile	Rabi 25 per-centile	Rabi 50 per-centile
1	2	3	4	5	6
1	Cauvery	990	1220	75	100
2	Chiklihole	52	65	4	6
3	Harangi	410	520	22	30
4	Lakshmanatheertha	67	90	7	10
5	Vetehole	68	81	6	9
6	Yagachi	320	405	21	25
7	Hemavathy	1130	1400	240	300
8	Cauvery Krishnarajasagar	1440	1800	310	400
9	Between Krishnarajasagar and Kabini	830	1100	110	150
10	Taraka	120	160	14	20
11	Hebballa	68	80	3	4
12	Kabini	1500	1900	162	200
13	Bandiganda (Sagare Doddakere)	33	47	6	10
14	Nugu	480	676	33	44
15	Kudregundi Halla	40	54	5	6
16	Devalapura	23	32	2	3
17	Gundlu (Nalluru Amani Kere)	80	115	7	10
18	Suvarnavathy	71	95	12	20

Table 5.12 (...Contd.)

1	2	3	4	5	6
19	Hebbahalla	8	10	0	2
20	Chikkahole	81	124	2	6
21	Upper Shimsha	550	740	60	80
22	Shimsha (Marcona Hally)	140	185	21	30
23	Mangala	24	34	3	6
24	Shimsha (Iggalur)	300	430	5	10
25	Kanva	30	440	3	5
26	Between Kabini & Shimsha	270	360	29	40
27	Gundal	17	25	0	2
28	Arkavathi (Chamarajasagar)	64	85	6	10
29	Arkavathi (Manchanabele)	60	80	5	10
30	Vrishabhavathi (Byramangala)	24	30	2	5
31	Arkavathi	150	220	7	10
32	Shimsha to Arkavathi	130	180	13	20
33	Thattehalla (Belthur)	25	38	2	5
34	Uduthorehalla	46	60	6	10
35	Thattehalla (Changawadi)	15	20	1	3
36	Doddihalla	9	12	1	3
37	Arkavathi to Boundary	120	150	21	30

Table 5.13

Power and Municipal & Industrial Demand

Sl. No.	Use point	Demand (100 Hect-m) Kharif	Rabi	Source
Power demand				
1	28	1000	1000	21
2	36	250	250	35
M&I demand				
3	23	15	15	21
4	27	15	15	21
5	80	83	82	35,79

supplies are taken as mandatory. These demands are met by specifying upper and lower bounds for arcs 181 through 184 (power) and arcs 185 through 188 (M&I supply) for kharif season; and for arcs 369 through 372 (power) and arcs 373 through 376 (M&I supplies) for rabi season, at the same level.

The demand for irrigation is assumed to be increasing at a specified schedule. It may be decided to bring certain hectares of arable area under irrigation under each project per year. These demands are introduced in the following statement

$$HI\ (arc) = HI\ (arc) + KI*(t - t_1)$$

This statement gives the role of increase of irrigable area KI and at what year t_1 the actual irrigation starts after the particular project is introduced into the system depending upon management policy and prevailing conditions. For each irrigation district one such statement is introduced. The maximum limit is specified by the statement of the following type

```
IF (HI (arc).GT.IR) HI(arc)  =  IR
```

where the IR is maximum irrigation facility under the project.

Table 5.13 gives the details of irrigation demands in Kharif and rabi seasons of the year.

Table 5.13

Irrigation demand

(100 Hect-m)

Sl. No.	Irrigation district	Season Kharif	Rabi	Source
1	2	3	4	5
1	4	175	115	1,2
2	6	259	123	5,19
3	10	16	16	9
4	12	30	20	11
5	14	100	44	13,16
6	18	260	140	17,16
7	20	280	193	8
8	22	650	535	21
9	25	1054	650	17,62
10	26	500	260	21,63
11	29	1000	1000	24
12	32	16	9	31
13	34	570	230	30,35
14	38	6	4	37
15	45	120	72	44
16	46	100	100	41
17	48	9	6	47
18	50	20	9	49
19	54	360	235	35,53
20	56	3	2	55

Table 5.13 (...Contd.)

1	2	3	4	5
21	59	12	8	58,
22	65	25	25	66,64
23	68	150	150	67
24	70	20	16	69
25	73	20	14	71
26	75	650	550	74
27	77	8	4	76
28	82	25	15	81,64
29	84	15	15	83
30	87	40	20	86
31	92	32	20	89,90,91
32	94	16	9	93
33	96	4	2	95

Chapter 6

RESULTS, DISCUSSIONS AND CONCLUSIONS

As mentioned in Chapter 5, the following cases are considered in the analysis:

a) deterministic stream flows
(seasonal mean flows)

b) stochastic stream flows

c) model with evaporation losses

d) model with return flows.

All the above cases are studied for two discount rates namely, 3% and 4%. The operation, maintenance and replacement costs are taken into account as a certain percentage of capital costs such as 0.25 percent and 0.50 percent.

The system is a very large one, consisting of 33 surface reservoir projects and 3 well field projects. The network (of reservoirs, well field units, canals, river channels, irrigation districts, municipal and industrial use points and power houses) consists of 300 node points and 437 arcs in the case of two season model. Because of the size of the model and number of combinations studied, no attempt is made here to present all the results for all the cases considered. The results of

deterministic and stochastic models only are given in Appendix B.

A list of selected projects and their sequence of introduction into the system based on deterministic flows using a discount rate of 3% and a benefit rate of Rs.45/hect-m for irrigation is given in table 6.1. It can be seen from this table that all the reservoirs except upper Shimsha are selected to their maximum capacity. The levels of the reservoirs in the system at the end of different seasons are presented in table 6.2. The amount of water directed to irrigation districts in different seasons in case of deterministic and stochastic models is given in table 6.3 (see also tables B-4 and B-6). The irrigation districts whose requirements are not met fully are underlined.

It can be seen that in kharif season, in the case of both deterministic and stochastic models, the requirements of irrigation are met except in only one irrigation district (25). But in the case of rabi season, requirements are not fully met in many irrigation districts. For example, for the deterministic case, requirements of 25 are not met and in the stochastic case requirements of 25, 26, 29, 32, 34, 54, 59, 68, 70, 73, 84, 92, are not met. In the case of stochastic model, the final network configuration is given in table B-6. From the flow values in different arcs of the deterministic case with 3% discount rate (Table B-4), it can be seen that there is no probability of impounding more water upstream of Krishnarajasagar because of

Table 6.1

Selected projects and their sequence of introduction into the system

(deterministic case, discount rate 3%)

Sl. No.	Project	Node No.	Reser-voir No.	Capacity (100 Hect-m)	Year of intro-duction	Notation*
1	2	3	4	5	6	7
1	Sagaredoddakere	37	29	6.00	1	29,1
2	Well units	64	43	20.00	2	43,2
3	Yagachi	13	23	27.00	3	23,3
4	Upper Shimsha	62	42	40.00	4	42,4
5	Harangi	5	17	183.00	5	17,5
6	Well unit	16	25	35.00	6	25,6
7	Uduthorehalla	90	53	22.00	7	53,7
8	Taraka	30	27	74.00	8	27,8
9	Arkavathi	86	49	42.00	9	49,9
10	Hosapatna	1	13	145.00	10	13,10
11	Gundal	76	47	30.00	11	47,11
12	Suvarnavathy	53	37	31.00	12	37,12
13	Well unit	91	55	20.00	13	55,13
14	Vetehole	11	21	28.00	14	21,14
15	Iggalur	69	45	2.00	15	45,15
16	Nallur Amanikere	49	35	29.00	16	35,16
17	Chiklihole	2	15	6.00	17	15,17
18	Lakshmanatheertha	9	19	19.00	18	19,18

Table 6.1 (...Contd.)

1	2	3	4	5	6	7
19	Devalapura	47	33	7.00	19	33,19
20	Kudregundihalla	43	31	8.00	20	31,20
21	Belthur	89	51	5.00	21	51,21
22	Hebbadahalla	55	39	4.00	22	39,22
23	Changawadi	93	57	8.00	23	57,23
24	Doddihalla	95	59	4.00	24	59,24

Present value of net benefits = Rs. 0.11206×10^{10}

(Irrigation benefit rate Rs.45/Hect-m
Power water rate Rs.96/Hect-m
M&I Water supply rate Rs.1000/Hect-m

*In this column the first figure in each row indicates the project no. and the second figure indicates the year of introduction. For example, 29,1 means, project 29 is introduced into the system in the year 1.

Table 6.2

Reservoir contents at the end of the season
(in 100 Hect-m)

Node No.	Kharif (t_1)	Rabi (t_2)	Project
1	2	3	4
1	100	145	Hosapatna
2	2	6	Chikihole
5	90	183	Harangi
9	10	19	Lakshmanatheertha
11	12	28	Vetehole
13	8	27	Yagachi
16	20	60	Well unit
17	300	960	Hemavathy
21	600	1040	Krishnarajasagar
30	40	74	Taraka
31	6	11	Hebballa
35	350	541	Kabini
37	2	6	Sagaredoddahore
42	60	122	Nugu
43	3	8	Kudregundihalla
47	3	7	Devalapura
49	9	29	Nallure amani kore
53	8	31	Suvarnavathy
55	1	4	Hebbadahalla
58	5	10	Chikkahole

Table 6.2 (...Contd.)

1	2	3	4
62	12	40	Upper Shimsha
63	30	64	Marcona Hally
64	30	60	Well unit
66	3	7	Mangala
69	2	2	Iggalur
71	9	18	Kanva
76	8	30	Gundal
79	45	82	Chamarajasagar
81	20	39	Manchanabele
83	3	17	Byramangala
86	10	42	Arkavathi
89	2	5	Belthur
90	8	22	Uduthorehalla
91	10	35	Well unit
93	2	8	Changawadi
95	4	4	Doddihalla

Table 6.3

Quantity of water supplied to various irrigation districts against their demands (in 100 Hect-m)

(Sum indicates supply from more than one project)

Sl. No.	Irrigation district	Kharif season			Rabi season		
		Demand	Supply		Demand	Supply	
			Deterministic case	Stochastic case		Deterministic case	Stochastic case
1	2	3	4	5	6	7	8
1	4	175	158+17	158+17	115	105+10	105+8
2	6	259	49+210	49+210	123	33+90	33+90
3	10	16	16	16	16	16	16
4	12	30	30	30	20	20	20
5	14	100	100	100	44	44	44
6	18	260	225+35	225+35	140	115+25	115+25
7	20	280	280	280	223	193	97
8	22	650	650	650	535	510	20
9	25	1054	626+134	356+34	650	600+23	397+23
10	26	500	440+60	25+60	260	118+40	0+40
11	29	1000	1000	1000	1000	406	335
12	32	16	16	16	9	9	8
13	34	570	500+70	500+70	230	101+30	63+30
14	38	6	6	6	4	4	4
15	45	120	120	120	72	72	72
16	46	100	100	100	100	100	100
17	48	9	9	9	6	6	6
18	50	20	20	20	9	9	9

Table 6.3 (...Contd.)

1	2	3	4	5	6	7	8
19	54	360	300+60	300+43	235	0+35	0+35
20	56	3	3	3	2	2	2
21	59	12	12	12	8	8	7
22	65	25	5+20	5+20	25	5+20	5+20
23	68	150	150	150	150	110	82
24	70	20	20	20	16	16	5
25	73	20	20	20	14	14	12
26	75	650	650	650	550	550	550
27	77	8	8	1	4	4	4
28	82	25	15+10	15+10	15	5+10	5+10
29	84	15	15	15	15	14	14
30	87	40	40	40	20	20	20
31	92	57	32+20+5	5+20+32	45	21+4+20	4+20+20
32	94	16	16	13	9	9	8
33	96	4	4	4	2	2	2

the requirements of the reaches down stream of the dam. It implies that water resources are fully utilized. It is the same in case of stochastic flows also.

The values of decision variables, (section 3.4.1) are given in table 6.4. These values give the quantity of water that flows down the stream channels. In rabi season the value of for arcs 266, 270, 272, 277, 279, 281, 289, 294, 297, 304, 305 and 318 is zero indicating that these reaches go dry in rabi season, i.e., no water flows down the river channels from reservoirs Chiklihole, Yagachi, Lakshmanatheertha, Krishnarajasagar, Hebballa, Kabini, Devalapura, Suvarnavathi, Chikkahole, Iggalur and Changawadi. It can be seen from the table that the values of s for Krishnarajasagar, Hemavathy, Kabini, Suvarnavathi, Kanva, Gundal, Chamarajasagar, Byramangala and Uduthorehalla are less than the value of 0.40. Hence, it can be said that the available water resources are used efficiently in these cases.

Dual Variables

The values of for original network are zero for each arc ($_i$ = 0) and for final network the values are given in table 6.4. From these values it is evident that the valuesof dual variables y_{ij} for 150 arcs (table B-) are not equal to the value of corresponding unit rate of return per hect-m.

For original network configuration the value of dual variable y_{ij} is equal to unit rate of return, i.e., from

Table 6.4

Fractions of release (Ψ) which will flow down the stream

Project at node	Annual mean flows (deterministic) Kharif	Annual mean flows (deterministic) Rabi	Stochastic flows (25 percentile) Kharif	Stochastic flows (25 percentile) Rabi
1	2	3	4	5
1	0.385	0.275	0.82	0.125
2	0.720	0.000	0.660	0.000
5	0.805	0.930	0.850	0.710
9	0.800	0.158	0.725	0.000
11	0.540	0.200	0.420	0.80
13	0.740	0.000	0.670	0.000
17	0.198	0.170	0.210	0.350
21	0.130	0.000	0.000	0.000
30	0.445	0.445	0.186	0.360
31	0.790	0.400	0.350	0.000
35	0.360	0.000	0.200	0.000
37	0.830	0.670	0.790	0.600
42	1.000	1.000	1.000	1.000
43	1.000	1.000	1.000	1.000
47	0.670	0.140	0.520	0.000
49	0.780	0.700	0.670	0.670
53	0.166	0.186	0.000	0.000
55	0.570	0.600	0.400	0.330
58	0.900	0.270	0.840	0.000

Table 6.4 (...Contd.)

1	2	3	4	5
62	0.950	0.780	0.940	0.740
63	0.930	0.720	0.900	0.670
66	0.810	0.450	0.750	0.285
69	0.980	0.000	0.970	0.000
71	0.355	0.000	0.050	0.000
76	0.110	0.780	0.000	0.750
79	0.100	0.120	0.110	0.023
81	0.770	0.850	0.630	0.670
83	0.285	0.000	0.000	0.000
86	0.840	0.720	0.720	0.590
89	0.840	0.500	0.770	0.200
90	0.305	0.120	0.000	0.000
93	0.610	0.310	0.000	0.000
95	0.600	0.600	0.430	0.330

section 4.3 for those arcs for which the unit rate of return is Rs.45, we can write,

$$C_{ij} = \sigma_i - \sigma_j - 45 = -45$$

$$y_{ij} = \max(0, +45)$$

$$z_{ij} = \max(0, -45)$$

Thus for these arcs in original network system

$$y_{ij} = 45$$

For final network system the values of σ for 150 arcs (Table B-5) equal to 45. The value of dual variable is calculated for one of these arcs and its significance is discussed:

Consider the arc number 185,

from table B-3, $\sigma = 45$ and $b_{ij} = 1000$

Value of $C_{ij} = 45-0-1000 = -955$

and $y_{ij} = \max(0, -C_{ij})$

$= \max(0, 955)$

$y_{ij} = 955$

and $z_{ij} = \max(0, -955)$

$= 0$

Therefore, increase in supply in this arc by one unit increases the revenue by Rs.955. This can be seen by examining the network configuration around this arc. The arc 147 competes

(irrigation supply) for water with arc 185. Hence increase in flow in arc 185 by one unit decreases the flow in arc 147 by one unit. Hence the net increase in revenue is (1000-45) = Rs.955.

Similarly significance of dual variables for other arcs can be explained.

The final network configuration indicates the flow in the arcs 134 & 322, i.e., exit flows from the basin for Kharif and rabi seasons are 5090 & 629 units respectively, for deterministic flow model. (unit = 100 Hect-m). The corresponding values in stochastic model are 2378 units and 556 units. Using the stochastic values as criterion for decision, it can be said that the maximum value of mandatory releases without reducing the irrigation potential of the basin are 2378 units in kharif season and 556 units in rabi season. Any constraint to increase these values curtails the irrigation potential of the basin.

The differences between initial network configuration and final network configuration indicate (tables B-2 & B-3) the changes in reservoir conditions and irrigation supply. The values of higher and lower bounds change from zero to the values shown in the table indicating that the projects are introduced into the system.

The contingent project constraint is included by imposing a condition that Yagachi project is introduced before Vetehole

project is introduced into the system. Only the sequence of introduction of projects into the system is altered whereas, the size of projects remain the same as seen in table 6.5.

Sensitivity Analysis

As mentioned earlier several cases are studied. Results for each case run into about 30 pages of computer sheets and hence it is not possible to include all the results here. However, the optimal scheduling and sequencing of projects (not including the operation policy) for different cases is given in table 6.5.

It is observed that there is no change in selection of projects. This is because, the size of the projects remaining same even though there is a change in sequencing of selected projects.

Conclusions

It can be concluded that mathematical programming technique combining the branch and bound algorithm and out-of-Kilter algorithm is a powerful tool in the analysis of optimal investment policy and operating policy problems of water resources systems. The approach incorporates institutional and budgetary constraints such that it provides guidance to the policy makers.

Table 6.5 (...Contd.)

Case	1	2	3	4	5
	51,21	29,22	31,22	51,21	51,21
	39,22	39,23	39,23	39,22	39,22
	57,23	57,24	57,24	57,23	57,23
	59,24	59,25	59,25	59,24	59,24
Present value of net benefits in Rs.	0.81972 x 10^9	0.12201 x 10^{10}	0.10204 x 10^{10}	0.11023 x 10^{10}	0.81971 x 10^9

* In this case project at node 13 (Yagachi)is contingent with the project at node 11 (Vetehole)

Note Water rate: Rs./Hect-m.

The model presented in this study can be altered suitably to suit the special conditions of the region and can be employed to any complex water resources system - multi-purpose-multiproject system.

In the present study, the combinatorial programming technique is used for solving the complex water resources system taking stochastic nature of inflows and evaporation losses into consideration. The chance-constraint programming approach used in the model helps to decide the operational policy along with optimal scheduling and sequencing policy, for known levels of reliability of service conditions.

The application to Cauvery river basin is done more from a point of demonstrating the application of combinatorial programming technique with stochastic nature of inflows and evaporation losses taken into account rather than making any specific recommendations for the development of study area. The economic parameters and inflow data used for some of the streams in the basin are rather crude. Further, in some cases, the data had to be estimated because of paucity of data and secrecy attached to the available data due to inter-state disputes regarding sharing of waters. If complete data is available for any basin, then the model can be used for making managerial decisions.

Suggestions for Future Work

Reliable values of objective function coefficients are required for the analysis, especially information is needed regarding the benefits attached to various uses of water and various levels of water use.

The demand pattern has to be established suitably taking other related topics such as agricultural, socio-economic conditions into consideration. The model should be solved taking a month as a season to study the dynamic nature of supply and demands.

More vigorous treatment of the problem is to consider the change of costs and benefits of projects and discount rate with time.

APPENDIX A

WATER RATES FOR IRRIGATION, MUNICIPAL, INDUSTRIAL & POWER SUPPLIES

Irrigation Rates

The water rates are estimated in the following way :

The amount of consumptive use is worked out for each crop by Christianson formula. Then taking farm efficiency (0.7) and conveyance efficiency (0.7) into consideration, the total amount of diversion is calculated at the head works. These are given in Table A.1 along with the land revenues suggested by Irrigation Commission, 1972.

Table A.1

Amount of diverted water

Sl.No.	Crop	Amount of water in m	Rate, Rs/Hect
1	Sugarcane	3.90	150.00
2	Rice	2.15	110.00
3	Other crops	0.85	40.00

By knowing the extent of areas under different crops irrigated by existing projects the following area-wise distribution is assumed: Rice 50% of the area; sugarcane 30% of the area and other crops 20% of the area.

Then the average water rate is estimated as follows:

The rate per hect-m for each crop:

$$\text{Sugar cane} \quad \frac{150}{3.90} = 38.50$$

$$\text{Rice} \quad \frac{110}{2.15} = 51.00$$

$$\text{Other crops} \quad \frac{40}{0.85} = 47.20$$

The weighted average rate, therefore, is

$$38.50 \times 0.30 + 51.00 \times 0.50 + 47.20 \times 0.20 = 46.50$$

Based on the above value, in the analysis two rates, namely, Rs.45/Hect-m and Rs.50/Hect-m are used.

Municipal and Industrial Supply Rates

Municipal and industrial supply rates are worked out using the data of Bangalore Water Supply & Sewerage Board (BWSSB). The supply pattern is divided into a number of types depending upon the type of consumer (say domestic, hotels, etc.) and each type is sub-divided into different groups depending on amount of consumption and suitable weightage is given for calculating the rates. The following gives the details of water rate calculation

Table A-2

Type 1 supply (Regular domestic supply)

Sl.No.	Group depending upon the amount of consumption (unit - 1000 litres)	Rate	Weightage	Weighted rate
1	2	3	4	5 (3 x 4)
1	0-25	0.40	40%	0.16
2	25-50	0.30	40%	0.12
3	50-75	0.40	10%	0.04
4	75-100	0.60	5%	0.03
5	100 and above	0.80	5%	0.04
				0.39/1000 litres

Type 2 supply (Domestic supply where no property tax is collected)

1	0-25	0.25	40%	0.10
2	25-50	0.30	40%	0.12
3	50-75	0.40	15%	0.06
4	75-100	0.60	3%	0.018
5	100 and above	0.80	2%	0.016
				0.314/1000 litres

Type 3 supply (commercial and other such establishments)

1	0-10	0.80	40%	0.32
2	10-20	1.00	30%	0.30
3	20-40	1.50	20%	0.30
4	40-100	2.00	5%	0.10
5	100 and above	2.50	5%	0.125
				1.145/1000 litres

Giving the weightages of 0.50 for type 1, 0.45 for type 2 and 0.05 for type 3, the water rates for municipal and industrial supply have been worked out as follows

Type of supply	Rate	Weightage	Weighted rate
Type 1	0.39	50%	0.200
Type 2	0.314	45%	0.145
Type 3	1.145	5%	0.057
			0.392/1000 litres

The cost of treatment and supply are taken from BWSSB data. The value works out to be Rs.0.285/1000 litres. However, the details are not given here as they are very extensive. Thus, net water rate (municipal and industrial supply) works out to be 0.108/1000 litre (0.392-0.285). Hence the rate of Rs.1000/Hect-m is adopted in the analysis.

Power Water Rates

In the present analysis the head on the turbines is assumed to be constant and the load factor of 0.85 to 0.90 and transmission losses of 15% to 20% are taken in the analysis. By knowing the efficiency of generator and turbines, the amount of water required to develop a unit of power is calculated.

The power rates are taken from tariff schedule of Karnataka Electricity Board (1974).

As in the case of municipal and industrial supply, the type of consumers are divided into number of categories depending upon the type of use (domestic or commercial) and the amount of consumption.

Type of consumers

High tension supply

Type	Details
A	Industries, water and sewerage pumping, railway workshops etc.
B	Hotels, railway stations, etc.
C	Irrigation pumps and other farm machinery
D	Research institutions and laboratories
E	Seasonal industries
F	Other high tension consumers
G	Rural electric cooperatives

Low tension supply

1	Residential supply (regular)
2	Residential supply (all electric)
3	Commercial supply

For all these types the unit rate of water (Rs/Hect-m) is worked out. The weighted average rate is taken in the analysis. (Table A-3)

Table A-3

Water rates for Power Generation

Type	Rate(Rs./Hect-m)	Weightage in percent	Weighted rate
A,C,D,E	55.00	20	11.06
B	100.00	20	20.00
F	69.00	20	13.80
G	46.00	20	9.20
1	235.00	10	23.50
2	68.00	5	3.40
3	290.00	5	14.50
			96.40

The value of Rs. 96/Hect-m is used in the analysis.

APPENDIX B

Table B-1

Details of Network

Arcs	Remarks
Kharif season	
1-40	Inflows
41-76	Reservoir initial conditions
77-134	Regulated flows
135-180	Irrigation flows
181-188	Power and M&I flows
Rabi season	
189-224	Reservoir initial conditions
225-264	Inflows
265-322	Regulated flows
323-368	Irrigation flows
369-376	Power & M&I flows
377-412	Final reservoir conditions
413-437	Exit flows

Table 3-2

Operating Policy

Original network configuration

(All units are in 100 Hect-m)

Arc	Source	Sink	Benefit rate (Rs/Hect-m)	Upper bound	Lower bound	Flow	Remarks
				Deterministic model			
1	2	3	4	5	6	7	8
1	299	1	0	1220	1220	1220	
2	299	2	0	65	65	65	
3	299	5	0	520	520	520	
4	299	9	0	90	90	90	
5	299	11	0	81	81	81	
6	299	13	0	405	405	405	
7	299	16	0	35	35	35	
8	299	17	0	1400	1400	1400	
9	299	21	0	1800	1800	1800	
10	299	24	0	1100	1100	1100	
11	299	30	0	160	160	160	
12	299	31	0	80	80	80	
13	299	35	0	1900	1900	1900	
14	299	37	0	47	47	47	Inflows
15	299	42	0	676	676	676	
16	299	43	0	54	54	54	
17	299	47	0	32	32	32	
18	299	49	0	115	115	115	
19	299	53	0	95	95	95	
20	299	55	0	11	11	11	
21	299	58	0	124	124	124	
22	299	62	0	740	740	740	
23	299	63	0	185	185	185	
24	299	64	0	40	40	40	
25	299	66	0	34	34	34	
26	299	69	0	430	430	430	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
27	299	71	0	40	40	40	
28	299	74	0	360	360	360	
29	299	76	0	25	25	25	
30	299	79	0	85	85	85	
31	299	81	0	80	80	80	
32	299	83	0	30	30	30	
33	299	86	0	220	220	220	
34	299	88	0	180	180	180	
35	299	89	0	38	38	38	
36	299	90	0	60	60	60	
37	299	91	0	20	20	20	Inflows
38	299	93	0	20	20	20	
39	299	95	0	12	12	12	
40	299	99	0	150	150	150	
41	299	1	0	0	0	0	
42	299	2	0	0	0	0	
43	299	5	0	0	0	0	
44	299	9	0	0	0	0	
45	299	11	0	0	0	0	
46	299	13	0	0	0	0	
47	299	16	0	0	0	0	
48	299	17	0	300	300	300	
49	299	21	0	600	600	600	
50	299	30	0	0	0	0	
51	299	31	0	6	6	6	
52	299	35	0	350	350	350	
53	299	37	0	0	0	0	
54	299	42	0	60	60	60	
55	299	43	0	0	0	0	
56	299	47	0	0	0	0	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
57	299	49	0	0	0	0	
58	299	53	0	0	0	0	
59	299	55	0	0	0	0	
60	299	58	0	5	5	5	
61	299	62	0	0	0	0	
62	299	63	0	30	30	30	
63	299	64	0	0	0	0	
64	299	66	0	3	3	3	
65	299	69	0	0	0	0	
66	299	71	0	9	9	9	Initial reservoir conditions (Kharif)
67	299	76	0	0	0	0	
68	299	79	0	45	45	45	
69	299	81	0	20	20	20	
70	299	83	0	8	8	8	
71	299	86	0	0	0	0	
72	299	89	0	0	0	0	
73	299	90	0	0	0	0	
74	299	91	0	0	0	0	
75	299	93	0	0	0	0	
76	299	95	0	0	0	0	
77	1	3	0	2000	0	1188	
78	2	3	0	100	0	63	
79	3	7	0	2100	0	1251	Regulated flows
80	5	7	0	800	0	495	
81	7	8	0	2500	0	1746	
82	9	9	0	100	0	80	
83	11	15	0	100	0	81	
84	13	15	0	510	0	387	
85	15	17	0	650	0	468	
86	17	19	0	2000	0	1568	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
87	19	8	0	1600	0	1358	
88	8	21	0	4400	0	2904	
89	21	24	0	4600	0	2964	
90	30	33	0	180	0	144	
91	31	33	0	90	0	65	
92	33	40	0	320	0	209	
93	35	39	0	1250	0	1010	
94	37	39	0	50	0	39	
95	39	40	0	1450	0	1299	
96	40	41	0	1800	0	1508	
97	42	44	0	800	0	576	
98	43	44	0	65	0	48	
99	44	41	0	670	0	504	
100	41	52	0	2020	0	1912	
101	47	51	0	38	0	28	
102	49	51	0	135	0	96	
103	51	52	0	180	0	124	Regulated flow
104	52	24	0	2500	0	2036	
105	24	61	0	6800	0	5000	
106	53	57	0	120	0	86	
107	55	57	0	20	0	9	
108	57	60	0	190	0	95	
109	58	60	0	190	0	85	
110	60	61	0	205	0	180	
111	61	74	0	7250	0	5180	
112	62	63	0	800	0	656	
113	63	67	0	820	0	768	
114	66	67	0	30	0	21	
115	67	69	0	740	0	639	
116	69	72	0	1230	0	991	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
117	71	72	0	35	0	16	
118	72	74	0	2200	0	1007	
119	74	78	0	9030	0	7507	
120	76	78	0	45	0	21	
121	78	88	0	9225	0	7527	
122	79	81	0	60	0	33	
123	81	85	0	155	0	80	
124	83	85	0	25	0	13	
125	85	86	0	180	0	93	Regulated flows (Kharif)
126	86	88	0	530	0	277	
127	88	99	0	10250	0	7964	
128	89	93	0	60	0	30	
129	90	98	0	60	0	52	
130	93	97	0	65	0	47	
131	95	97	0	25	0	11	
132	97	98	0	105	0	58	
133	98	99	0	210	0	110	
134	99	100	0	12430	0	8209	
135	1	4	45	0	0	0	
136	2	4	45	0	0	0	
137	5	6	45	0	0	0	
138	9	10	45	0	0	0	
139	11	12	45	0	0	0	
140	13	14	45	0	0	0	Irrigation flows
141	16	14	45	0	0	0	
142	16	18	45	0	0	0	
143	17	18	45	260	260	260	
144	17	25	45	0	0	0	
145	19	6	45	210	210	210	
146	8	20	45	280	280	280	
147	21	22	45	650	650	650	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
148	21	26	45	0	0	0	
149	30	34	45	0	0	0	
150	31	32	45	16	16	16	
151	35	34	45	500	500	500	
152	35	54	45	0	0	0	
153	37	38	45	0	0	0	
154	44	45	45	120	120	120	
155	41	46	45	100	100	100	
156	47	48	45	0	0	0	
157	49	50	45	0	0	0	
158	24	29	45	1000	1000	1000	
159	53	54	45	0	0	0	
160	55	56	45	0	0	0	
161	58	59	45	12	12	12	
162	62	25	45	0	0	0	
163	63	26	45	60	60	60	
164	64	65	45	0	0	0	flows
165	64	32	45	0	0	0	
166	66	65	45	8	8	8	
167	67	68	45	150	150	150	
168	69	70	45	0	0	0	
169	71	73	45	20	20	20	
170	74	75	45	650	650	650	
171	76	77	45	0	0	0	
172	81	82	45	25	25	25	
173	83	84	45	15	15	15	
174	86	87	45	0	0	0	
175	89	92	45	0	0	0	
176	90	92	45	0	0	0	
177	91	92	45	0	0	0	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
178	91	96	45	0	0	0	
179	93	94	45	0	0	0	Irrigatio
180	95	96	45	0	0	0	
181	21	28	0	1000	1000	1000	
182	28	74	96	1000	1000	1000	Power supply
183	35	36	0	250	250	250	
184	36	39	96	250	250	250	
185	21	23	1000	15	15	15	
186	21	27	1000	15	15	15	M&I supply
187	35	80	1000	40	40	40	
188	79	80	1000	43	43	43	
189	1	151	0	0	0	0	
190	2	152	0	0	0	0	
191	5	155	0	0	0	0	
192	9	159	0	0	0	0	
193	11	161	0	0	0	0	
194	13	163	0	0	0	0	
195	16	166	0	0	0	0	
196	17	167	0	960	960	960	
197	21	171	0	1140	1140	1140	Initial reservoi conditio
198	30	180	0	0	0	0	
199	31	181	0	11	11	11	
200	35	185	0	541	541	541	
201	37	187	0	0	0	0	
202	42	192	0	122	122	122	
203	43	193	0	0	0	0	
204	47	197	0	0	0	0	
205	49	199	0	0	0	0	
206	53	203	0	0	0	0	
207	55	205	0	0	0	0	

Table B-2 (...Contd.

1	2	3	4	5	6	7	8
208	58	208	0	10	10	10	
209	62	212	0	0	0	0	
210	63	213	0	64	64	64	
211	64	214	0	0	0	0	
212	66	216	0	7	7	7	
213	69	219	0	0	0	0	
214	71	221	0	18	18	18	Initial reservoir condition
215	76	226	0	0	0	0	
216	79	229	0	82	82	82	
217	81	231	0	39	39	39	
218	83	233	0	17	17	17	
219	86	236	0	0	0	0	
220	89	239	0	0	0	0	
221	90	240	0	0	0	0	
222	91	241	0	0	0	0	
223	93	243	0	0	0	0	
224	95	245	0	0	0	0	
225	299	151	0	100	100	100	
226	299	152	0	5	5	5	
227	299	155	0	30	30	30	
228	299	159	0	10	10	10	
229	299	161	0	9	9	9	
230	299	163	0	25	25	25	
231	299	166	0	25	25	25	
232	299	167	0	300	300	300	Inflows
233	299	171	0	400	400	400	
234	299	174	0	150	150	150	
235	299	190	0	20	20	20	
236	299	181	0	4	4	4	
237	299	185	0	100	100	100	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
238	299	187	0	2	2	2	
239	299	192	0	72	72	72	
240	299	193	0	6	6	6	
241	299	197	0	3	3	3	
242	299	199	0	8	8	8	
243	299	203	0	20	20	20	
244	299	205	0	1	1	1	
245	299	208	0	6	6	6	
246	299	212	0	80	80	80	
247	299	213	0	30	30	30	
248	299	214	0	15	15	15	
249	299	216	0	2	2	2	
250	299	219	0	10	10	10	
251	299	221	0	5	5	5	
252	299	224	0	40	40	40	
253	299	226	0	2	2	2	Inflows
254	299	229	0	10	10	10	
255	299	231	0	10	10	10	
256	299	233	0	5	5	5	
257	299	236	0	10	10	10	
258	299	238	0	20	20	20	
259	299	239	0	2	2	2	
260	299	240	0	10	10	10	
261	299	241	0	20	20	20	
262	299	243	0	3	3	3	
263	299	245	0	3	3	3	
264	299	249	0	30	30	30	
265	151	153	0	132	132	132	
266	152	153	0	7	7	7	Regulate flows
267	153	157	0	139	139	139	
268	155	157	0	55	55	55	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
269	157	158	0	194	194	194	
270	159	158	0	20	20	20	
271	161	165	0	100	0	9	
272	163	165	0	510	0	43	
273	165	167	0	650	0	52	
274	167	169	0	2000	0	252	
275	169	158	0	1600	0	162	
276	153	171	0	4400	0	156	
277	171	174	0	4600	0	0	
278	180	183	0	180	0	36	
279	181	183	0	90	0	0	
280	183	190	0	320	0	36	
281	185	189	0	1250	0	0	
282	187	189	0	150	0	10	
283	189	190	0	1450	0	260	
284	190	191	0	1800	0	296	Regulated
285	192	194	0	500	0	144	flows
286	193	194	0	65	0	12	
287	194	191	0	670	0	84	
288	191	202	0	2020	0	280	
289	197	201	0	38	0	7	
290	199	201	0	135	0	24	
291	201	202	0	180	0	31	
292	202	174	0	2500	0	311	
293	174	211	0	6800	0	0	
294	203	207	0	120	0	29	
295	205	207	0	20	0	3	
296	207	210	0	190	0	92	
297	208	210	0	190	0	25	
298	201	211	0	205	0	57	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
299	211	224	0	7250	0	57	
300	212	213	0	800	0	164	
301	213	217	0	820	0	167	
302	216	217	0	30	0	1	
303	217	219	0	740	0	18	
304	219	222	0	1230	0	106	
305	221	222	0	35	0	0	
306	222	224	0	2200	0	106	
307	224	228	0	9030	0	693	
308	226	228	0	45	0	7	
309	228	238	0	9225	0	700	
310	229	231	0	60	0	0	Regulated flows
311	231	235	0	155	0	3	
312	233	235	0	25	0	0	
313	235	236	0	130	0	3	
314	236	238	0	530	0	49	
315	238	249	0	10250	0	789	
316	239	243	0	60	0	10	
317	240	248	0	60	0	18	
318	243	247	0	65	0	16	
319	245	247	0	25	0	4	
320	247	248	0	105	0	20	
321	248	249	0	210	0	38	
322	249	250	0	12430	0	872	
323	151	154	45	0	0	0	
324	152	154	45	0	0	0	
325	155	156	45	0	0	0	Irrigation flows
326	159	160	45	0	0	0	
327	161	162	45	0	0	0	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
328	163	164	45	0	0	0	
329	166	164	45	0	0	0	
330	166	168	45	0	0	0	
331	167	168	45	0	140	140	
332	167	175	45	0	0	0	
333	169	156	45	210	90	90	
334	158	170	45	280	220	220	
335	171	172	45	650	535	535	
336	171	176	45	0	0	0	
337	180	184	45	0	0	0	
338	181	182	45	16	9	9	
339	185	184	45	500	400	400	
340	185	204	45	0	0	0	
341	187	188	45	0	0	0	
342	194	195	45	120	72	72	
343	191	196	45	100	100	100	Irrigation flows
344	197	198	45	0	0	0	
345	199	200	45	0	0	0	
346	174	179	45	1000	1000	1000	
347	203	204	45	0	0	0	
348	205	206	45	0	0	0	
349	208	209	45	12	8	8	
350	212	175	45	0	0	0	
351	213	176	45	60	40	40	
352	214	215	45	30	0	0	
353	214	232	45	30	0	0	
354	216	215	45	8	6	6	
355	217	218	45	150	150	150	
356	219	220	45	0	0	0	
357	221	223	45	20	14	14	
358	224	225	45	650	550	550	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
359	226	227	45	0	0	0	Irrigation flows
360	231	232	45	25	15	15	
361	233	234	45	15	15	15	
362	236	237	45	0	0	0	
363	239	242	45	0	0	0	
364	240	242	45	0	0	0	
365	241	241	45	0	0	0	
366	241	246	45	0	0	0	
367	243	244	45	0	0	0	
368	245	246	45	0	0	0	
369	171	178	0	1000	1000	1000	Power supply (Rabi season)
370	178	224	96	1000	1000	1000	
371	185	186	0	250	250	250	
372	186	189	96	250	250	250	
373	171	173	1000	15	15	15	M&I supply (Rabi season)
374	171	177	1000	15	15	15	
375	185	230	1000	40	40	40	
376	229	230	1000	42	42	42	
377	151	300	0	0	0	0	Final reservoir condition
378	152	300	0	0	0	0	
379	155	300	0	0	0	0	
380	159	300	0	0	0	0	
381	161	300	0	0	0	0	
382	163	300	0	0	0	0	
383	166	300	0	0	0	0	
384	167	300	0	300	300	300	
385	171	300	0	600	600	600	
386	180	300	0	0	0	0	
387	181	300	0	6	6	6	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
388	185	300	0	350	350	350	
389	187	300	0	0	0	0	
390	192	300	0	60	60	60	
391	193	300	0	0	0	0	
392	197	300	0	0	0	0	
393	199	300	0	0	0	0	
394	203	300	0	0	0	0	
395	205	300	0	0	0	0	
396	208	300	0	5	5	5	
397	212	300	0	0	0	0	Final reservoir conditions (Rabi season)
398	213	300	0	30	30	30	
399	214	300	0	0	0	0	
400	216	300	0	3	3	3	
401	219	300	0	0	0	0	
402	221	300	0	9	9	9	
403	226	300	0	0	0	0	
404	229	300	0	45	45	45	
405	231	300	0	20	20	20	
406	233	300	0	8	8	8	
407	236	300	0	0	0	0	
408	239	300	0	0	0	0	
409	240	300	0	0	0	0	
410	241	300	0	0	0	0	
411	243	300	0	0	0	0	
412	245	300	0	0	0	0	
413	4	300	0	0	0	0	
414	6	300	0	0	0	0	
415	10	300	0	0	0	0	Exit flows
416	12	300	0	0	0	0	
417	14	300	0	0	0	0	
418	18	300	0	0	0	0	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
419	20	300	0	0	0	0	
420	22	300	0	0	0	0	
421	25	300	0	0	0	0	
422	26	300	0	500	0	60	
423	29	300	0	1000	0	1000	
424	32	300	0	16	0	16	
425	34	300	0	570	0	500	
426	38	300	0	0	0	0	
427	45	300	0	120	0	120	
428	46	300	0	100	0	100	
429	48	300	0	0	0	0	
430	50	300	0	0	0	0	
431	54	300	0	0	0	0	
432	56	300	0	3	0	3	
433	59	300	0	12	0	12	Exit flows
434	65	300	0	48	0	8	
435	68	300	0	150	0	150	
436	70	300	0	0	0	0	
437	73	300	0	20	0	20	
438	75	300	0	650	0	650	
439	77	300	0	0	0	0	
440	82	300	0	60	0	25	
441	84	300	0	15	0	15	
442	87	300	0	40	0	0	
443	92	300	0	0	0	0	
444	94	300	0	0	0	0	
445	96	300	0	0	0	0	
446	100	300	0	8209	0	8209	
447	23	300	0	15	0	15	
448	27	300	0	15	0	15	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
449	80	300	0	83	0	83	
450	154	300	0	115	0	105	
451	156	300	0	0	0	0	
452	160	300	0	0	0	0	
453	162	300	0	0	0	0	
454	164	300	0	0	0	0	
455	168	300	0	165	0	140	
456	170	300	0	220	0	220	
457	172	300	0	535	0	535	
458	175	300	0	0	0	0	
459	176	300	0	268	0	40	
460	179	300	0	1000	0	1000	
461	182	300	0	9	0	9	
462	184	300	0	430	0	400	
463	188	300	0	0	0	0	
464	195	300	0	120	0	72	
465	196	300	0	100	0	100	
466	198	300	0	0	0	0	
467	200	300	0	0	0	0	
468	204	300	0	0	0	0	
469	206	300	0	0	0	0	
470	209	300	0	8	0	3	
471	215	300	0	21	0	6	
472	218	300	0	213	0	150	
473	220	300	0	0	0	0	
474	223	300	0	0	0	0	
475	225	300	0	550	0	550	
476	227	300	0	0	0	0	

Table B-2 (...Contd.)

1	2	3	4	5	6	7	8
477	232	300	0	30	0	15	
478	234	300	0	15	0	15	
479	237	300	0	0	0	0	
480	242	300	0	0	0	0	Exit
481	244	300	0	0	0	0	flows
482	246	300	0	0	0	0	
483	173	300	0	15	0	15	
484	177	300	0	15	0	15	
485	230	300	0	40	0	40	
486	250	300	0	872	0	872	
487	300	299	0	20731	0	16308	

Table B-3

Value of σ

Arcs	σ	
1-487	0	Initial network

Table B.4

Operating policy

The final network configuration

(Deterministic flows, discount rate 3%)

Arc	Source	Sink	Benefit rate (Rs/Hect-m)	Upper bound	Lower bound	Flow	Remarks
1	2	3	4	5	6	7	8
1 . . . 40	299 . . . 299	1 . . . 99	0 . . . 0	1220 . . . 150	1220 . . . 150	1220 . . . 150	Inflows as given in Table 5.
41	299	1	0	100	100	100	
42	299	2	0	2	2	2	
43	299	5	0	90	90	90	
44	299	9	0	10	10	10	
45	299	11	0	12	12	12	
46	299	13	0	8	8	8	
47	299	16	0	20	20	20	
48	299	17	0	400	400	400	
49	299	21	0	600	600	600	
50	299	30	0	40	40	40	
51	299	31	0	6	6	6	
52	299	35	0	350	350	350	Reservoir initial condition
53	299	37	0	2	2	2	
54	299	42	0	60	60	60	
55	299	43	0	3	3	3	
56	299	47	0	3	3	3	
57	299	49	0	9	9	9	
58	299	53	0	8	8	8	
59	299	55	0	1	1	1	
60	299	58	0	5	5	5	
61	299	62	0	12	12	12	

Table B-4 (...Contd.)

1	2	3	4	5	6	7	8
62	299	63	0	30	30	30	
63	299	64	0	30	30	30	
64	299	66	0	3	3	3	
65	299	69	[illegible]	2	2	2	
66	299	71	0	9	9	9	
67	299	76	0	8	8	8	Initial reservoir conditions
68	299	79	0	45	45	45	
69	299	81	0	20	20	20	
70	299	83	0	8	8	8	
71	299	86	0	10	10	10	
72	299	89	0	2	2	2	
73	299	90	0	[illegible]	8	8	
74	299	91	0	10	10	10	
75	299	93	0	2	2	2	
76	299	95	0	2	2	2	
77	1	3	0	2000	0	1188	
78	2	3	0	100	0	44	
79	3	7	0	2100	0	1016	
80	5	7	0	300	0	373	
81	7	8	0	2500	0	1394	
82	9	8	0	100	0	65	
83	11	15	0	100	0	35	Regulated flows
84	13	15	0	510	0	286	
85	15	17	0	650	0	321	
86	17	19	0	2000	0	210	
87	19	8	0	1600	0	0	
88	8	21	0	4400	0	1179	
89	21	24	0	4600	0	2978	
90	30	33	0	180	0	56	
91	31	33	0	90	0	59	

Table 5-4 (...Contd.)

1	2	3	4	5	6	7	8
92	33	40	0	320	0	115	
93	35	39	0	1250	0	619	
94	37	39	0	50	0	30	
95	39	40	0	1450	0	899	
96	40	41	0	1800	0	1014	
97	42	44	0	800	0	614	
98	43	44	0	65	0	49	
99	44	41	0	670	0	543	
100	41	52	0	2020	0	1457	
101	47	51	0	33	0	19	
102	49	51	0	135	0	70	
103	51	52	0	180	0	89	
104	52	24	0	2500	0	1546	
105	24	61	0	6800	0	1965	
106	53	57	0	120	0	12	
107	55	57	0	20	0	4	
108	57	60	0	190	0	16	
109	58	60	0	190	0	107	
110	60	61	0	205	0	123	
111	61	74	0	7250	0	2088	
112	62	63	0	800	0	678	
113	63	67	0	920	0	769	
114	66	67	0	30	0	21	
115	67	59	0	740	0	640	
116	69	72	0	1230	0	1050	
117	71	72	0	35	0	11	
118	72	74	0	2200	0	1061	
119	74	78	0	7030	0	4509	
120	76	78	0	45	0	1	
121	78	88	0	9225	0	4510	
122	79	81	0	60	0	5	
123	81	85	0	155	0	41	

Table B-4 (...Contd.)

1	2	3	4	5	6	7	8
124	83	85	0	25	0	6	
125	85	86	0	180	0	47	
126	86	88	0	530	0	195	
127	88	99	0	10250	0	4895	
128	89	93	0	60	0	27	Regulated
129	90	98	0	60	0	14	flows
130	93	97	0	65	0	25	
131	95	99	0	25	0	6	
132	97	98	0	105	0	31	
133	98	99	0	210	0	45	
134	99	100	0	12430	0	5090	
135	1	4	45	158	0	158	
136	2	4	45	17	0	17	
137	5	6	45	49	0	49	
138	9	10	45	16	0	16	
139	11	12	45	30	0	30	
140	13	14	45	100	0	100	
141	16	14	45	0	0	0	
142	16	18	45	35	0	35	Irrigation
143	17	18	45	220	220	220	flows
144	17	25	45	626	0	626	
145	19	6	45	210	210	210	
146	8	20	45	280	280	280	
147	21	22	45	650	650	650	
148	21	26	45	440	0	440	
149	30	34	45	70	0	70	
150	31	32	45	16	16	16	
151	35	34	45	500	500	500	
152	35	54	45	300	0	300	
153	37	38	45	6	0	6	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
154	44	45	45	120	120	120	
155	41	46	45	100	100	100	
156	47	48	45	9	0	9	
157	49	50	45	20	0	20	
158	24	29	45	1000	1000	1000	
159	51	54	45	60	0	60	
160	55	56	45	3	0	3	
161	58	59	45	12	12	12	
162	62	25	45	34	0	34	
163	63	26	45	60	60	60	
164	64	65	45	20	0	20	
165	64	82	45	10	0	10	
166	66	65	45	5	0	5	
167	67	68	45	150	150	150	
168	69	70	45	20	0	20	
169	71	73	45	20	20	20	
170	74	75	45	650	650	650	
171	76	77	45	8	0	8	
172	81	82	45	15	15	15	
173	83	84	45	15	15	15	
174	86	87	45	40	0	40	
175	89	92	45	5	0	5	
176	90	92	45	32	0	32	
177	91	92	45	20	0	20	
178	91	96	45	0	0	0	
179	93	94	45	16	0	16	
180	95	96	45	4	0	4	
181	21	28	0	1000	1000	1000	
182	28	74	96	1000	1000	1000	
183	35	36	0	250	250	250	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
184	36	39	96	250	250	250	Power supply
185	21	23	1000	15	15	15	
186	21	27	1000	15	15	15	M & I aupply
187	35	80	1000	40	40	40	
188	79	80	1000	43	43	43	
189	1	151	0	145	145	145	
190	2	152	0	6	6	4	
191	5	155	0	183	183	93	
192	9	159	0	19	19	9	
193	11	161	0	28	28	16	
194	13	163	0	27	8	19	
195	16	166	0	20	20	20	
196	17	167	0	960	400	560	
197	21	171	0	1140	600	540	
198	30	180	0	74	74	34	
199	31	181	0	11	6	5	
200	35	185	0	541	350	191	Reservoir initial condition
201	37	187	0	6	2	4	
202	42	192	0	122	60	62	
203	43	193	0	8	8	5	
204	47	197	0	7	7	4	
205	49	199	0	29	29	20	
206	53	203	0	31	31	23	
207	55	205	0	4	4	3	
208	58	208	0	10	5	5	
209	62	212	0	40	12	28	
210	63	213	0	64	30	34	
211	64	214	0	60	30	30	
212	66	216	0	7	3	4	
213	69	219	0	2	2	0	
214	71	221	0	18	9	9	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
215	76	226	0	24	8	16	
216	79	229	0	82	45	37	
217	81	231	0	39	20	19	
218	83	233	0	17	8	9	
219	86	236	0	42	42	32	Reservoir initial conditions
220	89	239	0	5	5	3	
221	90	240	0	22	22	14	
222	91	241	0	35	20	10	
223	93	243	0	8	8	6	
224	95	245	0	0	0	0	
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	Inflows (Table 5.12)
.	.	.	.	.	.	.	
265	151	153	0	132	132	40	
266	152	153	0	7	7	0	
267	153	157	0	139	139	40	
268	155	157	0	55	55	90	
269	157	158	0	194	194	130	
270	159	158	0	20	20	3	
271	161	165	0	100	0	5	
272	163	165	0	510	0	0	
273	165	167	0	650	0	5	
274	167	169	0	2000	0	125	
275	169	158	0	1600	0	60	Regulated flows
276	158	171	0	4400	0	0	
277	171	174	0	4600	0	0	
278	180	183	0	180	0	24	
279	181	183	0	90	0	6	
280	183	190	0	320	0	30	
281	185	189	0	1250	0	0	
282	187	189	0	150	0	9	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
283	189	190	0	1450	0	259	
284	190	191	0	1800	0	289	
285	192	194	0	500	0	106	
286	193	194	0	65	0	11	
287	194	191	0	670	0	45	
288	191	202	0	2020	0	234	
289	197	201	0	38	0	1	
290	199	201	0	135	0	21	
291	201	202	0	180	0	22	
292	202	174	0	2500	0	256	
293	174	211	0	6800	0	0	
294	203	207	0	120	0	8	
295	205	207	0	20	0	3	Regulated
296	207	210	0	190	0	11	flows
297	208	210	0	190	0	3	
298	210	211	0	205	0	14	
299	211	224	0	7250	0	14	
300	212	213	0	800	0	85	
301	213	217	0	820	0	109	
302	216	217	0	30	0	4	
303	217	219	0	740	0	0	
304	219	222	0	1230	0	0	
305	221	222	0	35	0	0	
306	222	224	0	2200	0	0	
307	224	228	0	9030	0	504	
308	226	228	0	45	0	14	
309	228	230	0	9225	0	518	
310	229	231	0	60	0	5	
311	231	235	0	155	0	19	
312	233	235	0	25	0	0	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
313	235	236	0	180	0	19	
314	236	238	0	530	0	41	
315	238	249	0	10250	0	579	
316	239	243	0	60	0	4	
317	240	248	0	60	0	3	Regulated flows
318	243	247	0	65	0	4	
319	245	247	0	25	0	3	
320	247	248	0	105	0	7	
321	248	249	0	210	0	10	
322	249	250	0	12430	600	629	
323	151	154	45	105	0	105	
324	152	154	45	10	0	10	
325	155	156	45	33	0	33	
326	159	160	45	16	0	16	
327	161	162	45	20	0	20	
328	163	164	45	44	0	44	
329	166	164	45	20	0	[illegible]	
330	166	168	45	20	0	35	
331	167	168	45	260	140	140	
332	167	175	45	380	0	340	
333	169	156	45	210	90	90	Irrigation flows
334	158	170	45	280	220	220	
335	171	172	45	650	200	510	
336	171	176	45	228	0	0	
337	180	184	45	30	0	30	
338	181	182	45	16	9	9	
339	185	184	45	500	50	101	
340	185	204	45	200	0	0	
341	187	188	45	4	0	4	
342	194	195	45	120	72	72	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
343	191	196	45	100	100	100	
344	197	198	45	6	0	6	
345	199	200	45	9	0	9	
346	174	179	45	1000	[illegible]	406	
347	203	204	45	35	0	35	
348	205	206	45	2	0	2	
349	208	209	45	12	8	8	
350	212	175	45	23	0	23	
351	213	176	45	60	40	40	
352	214	215	45	30	0	20	
353	214	232	45	30	0	10	Irrigation flows
354	216	215	45	8	3	5	
355	217	218	45	150	100	110	
356	219	220	45	16	0	12	
357	221	223	45	20	14	14	
358	224	225	45	650	100	106	
359	226	227	45	4	0	4	
360	231	232	45	25	0	5	
361	233	234	45	15	12	14	
362	236	237	45	20	0	20	
363	239	242	45	5	0	5	
364	240	242	45	21	0	21	
365	241	242	45	20	0	20	
366	241	246	45	20	0	0	
367	243	244	45	9	0	9	
368	245	246	45	2	0	2	
369	171	178	0	1000	1000	1000	
370	178	224	96	1000	1000	1000	Power flows
371	185	186	0	250	250	250	
372	186	189	96	250	250	250	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
373	171	173	1000	15	15	15	
374	171	177	1000	15	15	15	M & I flows
375	185	230	1000	40	40	40	
376	229	230	1000	42	42	42	
377	151	300	0	100	100	100	
378	152	300	0	2	2	2	
379	155	300	0	90	90	90	
380	159	300	0	10	10	10	
381	161	300	0	12	12	12	
382	163	300	0	8	8	8	
383	166	300	0	20	20	20	
384	167	300	0	300	300	300	
385	171	300	0	600	600	600	
386	180	300	0	40	40	40	
387	181	300	0	6	6	6	
388	185	300	0	350	350	350	
389	187	300	0	2	2	2	Reservoir final conditions
390	192	300	0	60	60	60	
391	193	300	0	3	3	3	
392	197	300	0	3	3	3	
393	199	300	0	9	9	9	
394	203	300	0	8	8	8	
395	205	300	0	1	1	1	
396	208	300	0	5	5	5	
397	212	300	0	12	12	12	
398	213	300	0	30	30	30	
399	214	300	0	30	30	30	
400	216	300	0	3	3	3	
401	219	300	0	2	2	2	
402	221	300	0	9	9	9	

Table B-4 (... Contd.)

1	2	3	4	5	6	7	8
403	226	300	0	8	8	8	
404	229	300	0	45	45	45	
405	231	300	0	20	20	20	
406	233	300	0	8	8	8	Final reser-
407	236	300	0	10	10	10	voir condition (Rabi season)
408	239	300	0	2	2	2	
409	240	300	0	8	8	8	
410	241	300	0	10	10	10	
411	243	300	0	2	2	2	
412	245	300	0	4	4	4	
413	4	300	0	115	0	112	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	Exit flows
487	300	299	0	20730	0	15404	

Table B. 5
Value of σ

Arcs	1-5	6	7-9	10	11	12
σ	0	45	0	45	0	45
Arcs	13	14	15	16	17	18
σ	0	45	0	45	0	45
Arcs	19	20	21	22	23-24	25
σ	0	45	0	45	0	45
Arcs	26-27	28	29-35	36	37	38
σ	0	45	0	45	0	45
Arcs	39-49	50	51-69	70	71-86	87
σ	0	45	0	45	0	45
Arcs	88-90	91-92	93	94	95	96
σ	0	45	0	45	0	45
Arcs	97-100	101-150	151-152	153	154-155	156-157
σ	0	45	0	45	0	45
Arcs	158-159	160	161	162	163	164
σ	0	45	0	45	0	45
Arcs	165-177	178	179-180	181	182-184	185-186
σ	0	45	0	45	0	45
Arcs	187	188	189-197	198	199	200
σ	0	45	0	45	0	45
Arcs	201-203	204	205	206	207-219	220221
σ	0	45	0	45	0	45
Arcs	222	223	224-226	227	228	229
σ	0	45	0	45	0	45
Arcs	230-232	233	234-236	237	238-240	241-242
σ	0	45	0	45	0	45
Arcs	243	244	245	246	247-250	251-298
σ	0	45	0	45	0	45
Arcs	299-487					
σ	0					

Table B-6

Operating Policy
The final network configuration
(Stochastic flows, discount rate 3%)

Arc	Source	Sink	Benefit rate ($/Hecm-m)	Upper bound	Lower bound	Flow	Remarks
1	2	3	4	5	6	7	8
1	299	1	0	990	990	990	Inflows as given in Table 3.11
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
41	299	1	0	100	100	100	Reservoir initial conditions
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
76	299	95	0	4	4	4	
77	1	3	0	2000	0	1042	
78	2	3	0	100	0	33	
79	3	7	0	2100	0	269	
80	5	7	0	800	0	775	
81	7	8	0	2500	0	1043	
82	9	8	0	100	0	42	
83	11	15	0	100	0	22	
84	13	15	0	510	0	201	
85	15	17	0	650	0	223	
86	17	19	0	2000	0	210	
87	19	8	0	1500	0	0	
88	8	21	0	4400	0	305	
89	21	24	0	4600	0	0	
90	30	33	0	180	0	16	
91	31	33	0	90	0	47	
92	33	40	0	320	0	63	
93	35	39	0	1250	0	219	

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8
94	37	39	0	50	0	23	
95	39	40	0	1450	0	492	
96	40	41	0	1800	0	555	
97	42	44	0	900	0	430	
98	43	44	0	55	0	35	
99	44	41	0	670	0	333	
100	41	53	0	2020	0	788	
101	47	51	0	30	0	10	
102	49	51	0	135	0	40	
103	51	52	0	180	0	50	
104	52	24	0	2500	0	838	
105	24	61	0	6800	0	668	Regulated flows
106	53	57	0	120	0	0	
107	55	57	0	20	0	2	
108	57	60	0	190	0	2	
109	58	60	0	190	0	64	
110	60	61	0	205	0	66	
111	61	74	0	7250	0	734	
112	62	63	0	800	0	483	
113	63	67	0	820	0	534	
114	66	67	0	30	0	15	
115	67	69	0	740	0	399	
116	69	72	0	1230	0	679	
117	71	72	0	35	0	1	
118	72	74	0	2200	0	680	
119	74	78	0	9030	0	2034	
120	76	78	0	45	0	0	
121	78	88	0	9225	0	2034	
122	79	81	0	60	0	0	
123	81	85	0	155	0	26	

Table 3-6 (...Contd.)

1	2	3	4	5	6	7	8
124	83	85	0	25	0	0	
125	85	86	0	180	0	26	
126	86	88	0	530	0	104	
127	87	89	0	10250	0	2268	
128	89	93	0	60	0	17	
129	90	93	0	60	0	0	
130	93	97	0	65	0	0	
131	95	97	0	25	0	3	
132	97	98	0	105	0	3	Regulated
133	98	99	0	210	0	0	flow
134	99	100	0	12430	1000	2391	
135	1	4	45	158	0	158	
136	2	4	45	17	0	17	
137	5	6	45	49	0	49	
138	7	10	45	16	0	16	
139	11	12	45	30	0	30	
140	13	14	45	100	0	100	
141	16	14	45	35	0	0	
142	16	18	45	35	0	0	
143	17	18	45	260	260	220	
144	17	25	45	1020	0	356	
145	19	6	45	210	210	210	
146	8	20	45	280	280	280	
147	21	22	45	650	650	650	
148	21	26	45	440	0	25	
149	30	34	45	70	0	70	
150	31	32	45	16	16	16	
151	35	34	45	500	500	500	
152	35	54	45	300	0	300	

Table B-6 (...Contd.)

1	2	3	4	5	6	7
153	37	38	45	[illegible]	0	6
154	44	45	45	120	120	120
155	41	46	45	100	100	100
156	47	[illegible]	45	[illegible]	0	9
157	49	[illegible]	45	20	0	20
158	24	25	45	1000	1000	1000
159	53	51	45	60	0	60
160	55	56	45	3	0	3
161	58	59	45	12	12	12
162	62	25	45	34	0	34
163	63	26	45	60	60	60
164	64	65	45	35	0	20
165	64	92	45	35	0	10
166	66	65	45	3	3	5
167	67	68	45	150	150	150
168	69	70	45	20	0	20
169	71	73	45	20	20	20
170	74	75	45	650	650	650
171	76	77	45	8	0	8
172	91	92	45	25	25	15
173	83	84	45	15	15	15
174	86	87	45	40	0	40
175	89	92	45	[illegible]	0	5
176	90	92	45	32	0	32
177	91	92	45	20	0	20
178	91	96	45	20	0	0
179	93	94	45	16	0	16
180	95	96	45	4	0	4
181	21	28	0	1000	1000	1000
182	28	74	96	1000	1000	1000

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8 ......
153	37	38	45	6	0	6	
154	44	45	45	120	120	120	
155	41	46	45	100	100	100	
156	47	48	45	9	0	9	
157	49	50	45	20	0	20	
158	24	29	45	1000	1000	1000	
159	53	54	45	60	0	60	
160	55	56	45	3	0	3	
161	58	59	45	12	12	12	
162	62	25	45	34	0	34	
163	63	26	45	60	60	60	
164	64	65	45	35	0	20	
165	64	82	45	35	0	10	
166	66	65	45	8	8	5	
167	67	68	45	150	150	150	
168	69	70	45	20	0	20	
169	71	73	45	20	20	20	
170	74	75	45	650	650	650	
171	76	77	45	8	0	8	
172	81	82	45	25	25	15	
173	83	84	45	15	15	15	
174	86	87	45	40	0	40	
175	89	92	45	8	0	5	
176	90	92	45	32	0	32	
177	91	92	45	20	0	20	
178	91	96	45	20	0	0	
179	93	94	45	16	0	16	
180	95	96	45	4	0	4	
181	21	28	0	1000	1000	1000	
182	28	74	96	1000	1000	1000	

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8
183	35	36	0	250	250	250	
184	36	39	96	250	250	250	
185	21	23	1000	15	15	15	
186	21	27	1000	15	15	15	
187	35	80	1000	40	40	40	
188	79	80	1000	43	43	43	
189	1	151	0	145	145	100	Reservoir initial condition rabi season
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
224	95	245	0	4	4	4	
225	299	151	0	110	110	75	Inflows rabi season
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
264	299	249	0	37	37	21	
265	151	153	0	2000	2000	15	
266	152	153	0	100	100	0	
267	153	157	0	2100	2100	15	
268	155	157	0	800	800	82	
269	157	158	0	2500	2500	97	
270	159	158	0	100	100	0	
271	161	165	0	100	0	2	
272	163	165	0	510	0	0	
273	165	167	0	650	0	2	
274	167	169	0	2000	0	290	
275	169	158	0	1600	0	200	
276	158	171	0	4400	0	200	
277	171	174	0	4600	0	0	
278	180	183	0	180	0	18	
279	181	183	0	90	0	0	
280	183	190	0	320	0	18	
281	185	189	0	1250	0	0	

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8
282	137	189	0	150	0	6	
283	189	190	0	1450	0	256	
284	190	191	0	1800	0	274	
285	192	194	0	500	0	95	
286	193	194	0	65	0	10	
287	194	191	0	670	0	33	
288	191	202	0	2020	0	207	
289	197	201	0	38	0	0	
290	199	201	0	135	0	18	
291	201	202	0	180	0	18	
292	202	174	0	2500	0	225	
293	174	211	0	6800	0	0	
294	203	207	0	120	0	0	
295	205	207	0	20	0	1	
296	207	210	0	190	0	1	
297	208	210	0	190	0	0	
298	210	211	0	205	0	1	
299	211	224	0	7250	0	1	
300	212	213	0	800	0	65	
301	213	217	0	820	0	80	
302	216	217	0	30	0	2	
303	217	219	0	740	0	0	
304	219	222	0	1230	0	0	
305	221	222	0	35	0	0	
306	222	224	0	2200	0	0	
307	224	228	0	9030	0	480	
308	226	228	0	45	0	12	
309	228	238	0	9225	0	492	
310	229	231	0	60	0	1	
311	231	235	0	155	0	10	
312	233	235	0	25	0	0	

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8
313	235	236	0	180	0	10	
314	236	238	0	530	0	29	
315	238	249	0	10250	0	534	
316	239	243	0	60	0	1	
317	240	248	0	60	0	0	
318	243	247	0	65	0	0	
319	245	247	0	25	0	1	
320	247	248	0	105	0	1	
321	248	249	0	210	0	1	
322	249	250	0	12430	0	556	
323	151	154	45	105	0	105	
324	152	154	45	10	0	8	
325	155	146	45	33	0	33	
326	159	160	45	16	0	16	
327	161	162	45	20	0	20	
328	163	164	45	44	0	40	
329	166	164	45	20	0	0	
330	166	168	45	20	0	25	
331	167	168	45	260	140	115	
332	167	175	45	380	0	397	
333	169	156	45	210	90	90	
334	158	170	45	280	220	97	
335	171	172	45	650	535	20	
336	171	176	45	228	0	0	
337	180	184	45	30	0	30	
338	181	182	45	16	9	8	
339	185	184	45	500	400	63	
340	185	204	45	200	0	0	
341	187	188	45	4	0	4	
342	194	195	45	120	72	72	

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8
343	191	196	45	100	100	100	
344	197	198	45	6	0	6	
345	199	200	45	9	0	9	
346	174	179	45	1000	1000	335	
347	203	204	45	35	0	35	
348	205	206	45	2	0	2	
349	208	209	45	12	8	7	
350	212	175	45	23	0	23	
351	213	176	45	60	40	40	
352	214	215	45	30	0	20	
353	214	232	45	30	0	0	
354	216	215	45	8	6	5	
355	217	218	45	150	82	82	
356	219	220	45	16	0	5	
357	221	223	45	20	14	12	
358	224	225	45	650	550	550	
359	226	227	45	4	0	4	
360	231	232	45	25	15	5	
361	233	234	45	15	15	14	
362	236	237	45	20	0	20	
363	239	242	45	4	0	5	
364	240	242	45	21	0	20	
365	241	242	45	30	0	20	
366	241	246	45	30	0	0	
367	243	244	45	9	0	8	
368	245	246	45	2	0	2	
369	171	178	0	1000	1000	1000	
370	178	224	96	1000	1000	1000	
371	185	186	0	250	250	250	
372	186	189	96	250	250	250	

Table B-6 (...Contd.)

1	2	3	4	5	6	7	8
373	171	173	1000	15	15	15	
374	171	177	1000	15	15	15	
375	185	230	1000	40	40	40	
376	229	230	1000	42	42	42	
377	151	300	0	100	100	100	Exit flows
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
.	.	.	.	.	.	.	
487	300	299	0	20731	0	16704	

Table B-7

Value of ∽

Arcs	1-3	4	5	6	7-9	10
∽	0	45	0	45	0	45
Arcs	11	12	13	14	15	16
∽	0	45	0	45	0	45
Arcs	17	18	19	20	21	22
∽	0	45	0	45	0	45
Arcs	23-24	25	26-27	28	29-35	36
∽	0	45	0	45	0	45
Arcs	37	38	39-47	48	49	50
∽	0	45	0	45	0	45
Arcs	51-53	54	55	56-69	70	71-76
∽	0	45	0	45	0	45
Arcs	77	78-86	87	88-90	91-92	93
∽	0	45	0	45	0	45
Arcs	94	95	96	97-100	101-150	151-152
∽	45	0	45	0	45	0
Arcs	153	154-155	156-157	158-159	160	161
∽	45	0	45	0	45	0
Arcs	162	163	164	165-177	178	179-180
∽	45	0	45	0	45	0
Arcs	181	182-184	185-186	187	188	189-197
∽	45	0	45	0	45	0
Arcs	198	199	200	201-203	204	205
∽	45	0	45	0	45	0
Arcs	206	207-219	220-221	222	223	224-226
∽	45	0	45	0	45	0
Arcs	227	228	229	230-232	233	234-236
∽	45	0	45	0	45	0
Arcs	237	238-240	241-242	243	244	245
∽	45	0	45	0	45	0
Arcs	246	247-250	251-298	299-487		
∽	45	0	45	0		

REFERENCES

Becker, L. and Yeh (1974). Optimal timing, sequencing a sizing of multiple reservoir surface water supply facilities. Water Resour. Res. 10(1), 57-65.

Butcher, W.S., Hall, W.A., and Haimes, Y.Y. (1969). Dyna programming for the optimal sequencing of water supp projects. Water Resour. Res. 5, 1196-1207.

Buras, N. (1972). Scientific allocation of water resourc Amer. Elsevier, New York.

Burton, R.M. (1969). A model for project selection in developing countries, 36th National ORSA meeting, Mi Florida.

BWSSB (1974). Bangalore Water Supply and Sewerage Board, Bangalore Water Supply Regulations, Karnataka Gazett (extraordinary), March 12, 1974.

Charnes, A., W.W. Cooper, and G. H. Symonds (1958). Cost horizon and certainty equivalents on approach to stochastic programming of heating oil. Management Science, 4(3), 235-263.

Chow, V.T., and Windsor, S. (1972). Multi reseroir optim tion model. Proc. A.S.C.E., 98, Hyd 10, 1827-1842.

CFF (1972). Report of the Cauvery fact finding Committe Ministry of Irrigation & Power, Government of India.

Chun, R.Y.D., et al. (1964). Ground Water management for nations future-optimum conjunctive operation of groun water basins. Proc. A.S.C.E., 90, Hyd. 4.

CW&PC (1955). A short note on increasing government inco by raising charges for water, Central Water and Power Commission, Ministry of Irrigation & Power, New Delhi

Dracup, J.A. (1966). Optimum use of ground-water and surface water system. A parametric linear programmin approach, Tech. Rep. 6-24, Hyd. Lab., Univ. Calif., Berkeley, Calif.

Ecstein, O. (1965). Water resources development, Harvard Univ. Press, Cambridge, Mass., 1965.

Fulkurson, D.R. (1961). An out of Kilter method for minimal cost flows, SIAM, J. Appl. Math., 18-27.

Hall, W.A. and Dracup, J.A. (1970). Water resources system engineering, McGraw-Hill, New York.

Hadley, G. (1964). Nonlinear and dynamic programming, Addison-Wesley, Reading, Mass., 1964.

Harbeck, G.E., Jr. (1966). Annual variability of lake evaporation, Int. Ass. Sci. Hydrol. (Garda), Publ.70(1), 294-303.

Hatfield & Pattison (1970). The conjunctive use of water resources. Proc. of Ground Water Symp., The Univ. of New South Wales, Australia. Ed. K. K. Watson.

Himmelblau, D.M. (1973). The optimal expansion of a water resources system. Final Technical Report, Dept. of Chem. Eng., Univ. Texas, Austin, Texas.

Hirshliefer et al. (1960). Water supply: Economics Technology and policy. Univ. Chicago Press, Chicago.

Hufschmidt, M.M. and Fiering, M.B. (1966). Simulation technique for design of water resource systems. Harvard Univ. Press, 1966.

KEB (1974). Karnataka Electricity Board. Electric Power Tariff

Kim, N.J. (1968). Linear programming with random requirements. Utah Water Res. Lab. Rep. PRWG 42-2T, Utah State Univ., Log

Koening, L. (1963). Economics of ground water utilization. Amer. Water Works Assoc. Jour. 55(1), 59-66.

Loucks (1969). Stochastic model for analyzing river basins. Water Resour. and Marine Sci. Center, Cornell Univ., Ithaca, New York.

Loucks (1968). Some comments on the optimization methods for branching multistage water resources systems. Water Resour Res. 4(2), 447-450.

Maass, et al. (1962). Design of water resources systems. Harvard Univ. Press, Cambridge, Mass.

Manne, A.S., (1962). Product mix alternatives. International Eco. Review, 3(1).

Manne, A.S., (1967). Investments for capacity expansions, size, location and time phasing, M.I.T. Press, Cambridge, Mass.

Mao, C.T. (1969). Quantitative analysis of financial decision: MacMillan, London.

Marglin, S.A. (1963). Approaches to dynamic investment planni: contribution to economic analysis, XXIX. Amsterdam, North-Holland Pub. Co.

Milligan, H. (1970). Optimizing conjunctive use of ground water and surface water. PRWG 42-4T, Utah Water Research Laboratory. Utah State University, Logan, Utah.

Morin, T.L. (1973). Optimal capacity expansion projects. Proc. ASCE 99. Hyd 9, 1605-1612.

Morin, T.L. and Esogbue, M.O. (1971). Some efficient dynamic programming algorithms for optimal sequencing and scheduli: of water supply projects. Water Res. Res. 7(3).

Morin, T.L. (1973). Pathology of a dynamic programming sequencing algorithm. Water Resour. Res. 9(5) 1178-85.

Mullvihill, M.H. and Dracup, J.A. (1974). Optimal timing and sizing of a conjunctive urban supply and waste water syster with non-linear programming. Water Resour. Res. 10(2), 170-

Nayak, S.C. and Arora, S.R. (1971). Optimal capacities of multireservoir system using the linear decision rule. Water Resour. Research. 7(3), 485-498.

Nayak, S.C. and Arora, S.R. (1970). A separable programming approach to the determination of optimal capacities, Water Resour. Res. 9(5), 1166-1185.

NCAER (1959). Criteria for fixation of water rates. National Council of Applied Economic Research, Asia Publishing House, New Delhi.

O'Lagaire, D.T. and Himmelbleau, D.M. (1971). Optimal capital investment in the expansion of an existing water resources system. Water Resour. Bull. 7(6), 1194-1209.

Orlob, G.T. (1970). Planning the Texas water system. Annu. Water Resour. Res. Conf. 5th, Washington, D.C., 1970, pp 171-186.

Raghava Rao, et al. (1969). An estimate of the ground water potential of India - First approximations. Soil & Water Management Symp., Hissar, March 1969.

Revelle, C. et al. (1969). The linear decision rule in reservo management and design, 1, Development of Stochastic model. Water Resour. Res. 5(4). 767-777.

Rogers, P. and D. V. Smith (1970). The integrated use of groun and surface waters in irrigation project planning. Amer. Jour. Agri. Eco. 52(1), 13-24.

TDWB (1968). The Texas water plan. Texas Water Development Board, Austin.

Tocher (1963). The art of simulation. The English University Press, London, 1963.

Trott, W. and Yeh, W.W.G. (1973). Optimization of multiple reservoir system. Proc. ASCE Hyd 10. 1865.

Tyson, H.N. and Weber, E.M. (1964). Computer simulation of ground water basins, Proc. ASCE 90, Hy 4,

U.P. Irrigation Commission (1959). Fixation of water rates - Commission report.

Veissman (1974). Elkhorn river sub-basin screening model. Wate Resour. Res. Ins. Univ. of Nebraska.

Viessman et al. (1975). A screening model for water resources planning. Water Resour. Bull. 11(2), 245-255.

Weingartner, H.M. (1967). Mathematical programming and the analysis of capital budgeting problems. Markham Pub. Co., Chicago.

Weiss and Beard (1971). A multi basin planning strategy. Water Resour. Bull. 7(4), 750-764.

Young, G.K., Mosely, J.C. and Evenson, D.E. (1969). Sequencing of element construction in a multi reservoir system. Water Resour. Bull. 6, 528-541.